HYDROCARBONS IN HUNGARY

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Hydrocarbons in Hungary

Results and opportunities

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Dear Reader,

One wouldn't have guessed that a book about Hungary's hydrocarbons would even be as weighty as a good miner's joke. On the other hand, you could at least say of miners' humour that it really exists! Or rather, it does, just not the way you would think.

Learned geology and petroleum engineering experts have debated on special social events of mining long into the night, whether Hungary has any worthwhile gas or oil fields. Then on the next day they start calling each other asking well, then, exactly what should they think about the new concession areas the ministry just offered up for bid? Do real resources exist in these concession areas, or do they not?

This book is an attempt to provide the answer to this question. It was written for those who have been taking great pains on behalf of the Hungarian common good, on behalf of communities, institutions, entrepreneurs, farmers and other Hungarians who think a very substantial share of Hungary's energy supply could be covered using domestic resources. Using domestic resources not only helps our country, but also saves it money, which of itself is a big issue in today's world. But the most important reason for using our own resources is that nobody can take it away from us, because it is right here under out feet.

In spite of a Hungarian hydrocarbon exploration and production history that stretches back more than a hundred years old, and more than 80 years after industrial quantities of petroleum were first discovered in Budafa, more and more new fields are still being discovered thanks to advanced exploration methods and technologies. These provide significant business profit to the prospecting and production companies and boost the national economy. Hydrocarbon occurrences in Hungary, combined with innovative and ever more efficient technical engineering methods, have allowed us today to set up a primary link in the global value chain, i.e., the energy resources of our homeland, which can then be coupled with the second link based on innovation and our own ideas, which can lead to a marketable product.

For whoever complains about energy scarcity here in the Carpathian Basin, we recommend this book. For all of our readers, we wish to pass along the traditional miners' greeting of "Jó szerencsét!", which means:

Good luck!

Attila Nyikos

Vice President of the Hungarian Energy and Public Utility Regulatory Authority in charge of International Affairs

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President of the Mining and Geological Survey of Hungary

Content

Historic overview of hydrocarbon exploration and production in Hungary

ZSOLT KOVÁCS, GYÖRGY PASZERA and ÁGNES GULYÁS

The beginning

Hungary's naturally occurring hydrocarbon accumulations have been used since the Middle Ages for chariot-axle lubrication, leather softening, waterproofing and lighting. Hydrocarbon exploration, mostly for natural asphalt ("bitumen") and crude oil ("petroleum"), began in the 1850s in what was then the territory of the Austro–Hungarian Monarchy. The bitumen sites of Sósmező (Transylvania) and Bányavár (Peklenica, Mura river valley) were known already by the end of the 18th century. Similar occurences were found in Tataros (1822), Dragomér (1839), Mikova and in what is now Croatia. Jakab Winterl, professor of chemistry at the University of Nagyszombat, published a 1788 thesis in Paris which analysed the Peklenica tar asphalt. This analysis of the oil of Peklenica was among the world's first such studies on this topic. The Hungarian Royal Geological Institute, founded in 1869, continued this academic tradition. Its geological mapping work and practical geological surveys, aided by the theoretical work of excellent university professors, heralded a significant era in Hungarian geological study. This greatly facilitated the exploration and utilisation of minerals and raw materials important for energy production. (FÜLÖP 1984).

For the first time from the current territory of Hungary BEUDANT (1822), and then TÓTH (1882) mentioned bitumen accumulation from Parád, the north-eastern region of Mátra Mountains, where it was used as a chariot axle lubricant. Matyasovszky in 1885 performed petroleum exploration at Recsk (MATYASOVSZKY 1885, POSEWITZ 1906). Posewitz mentioned that the Miocene rhyolite tuff at Recsk is saturated with bitumen. Between 1883 and 1899 the Hungarian Royal Geological Institute prepared a geological survey in the area of the then known petroleum traces, including Recsk. In 1885–88 at Recsk two contractors drilled three boreholes (to 132, 212, 162 metres), but due to lack of success the drilling was given up (POSEWITZ 1906). The expanding economic role of crude oil, the growing need for lubricating oil, lighting oil, and the rising fuel demand for gasoline motors stimulated research, along with successful oil exploration in Galatia and Romania, and well-known deposits of crude oil at several points in other parts of the country. The methods used to explore crude oil in historic Hungary were shafts and shallow depth wells. At Derna-Tataros asphalt (earth tar) was excavated from 1889, of which the annual production was nearly 1800 tons of crude oil. From 1893 on the state also supported the exploration but results remained low during the years after the turn of the century. The Hungarian "petroleum" production between 1860 and 1905 was 55,479 tons (POSEWITZ 1906). Nearly 80% of this was produced in Mura Valley and Croatia, 20% from Sáros, Zemplén, Ung and Máramaros counties. Significant results were realised only after the nationalisation of oil exploration, supported by qualified geologists using modern equipment and capital power.

At the end of the 19th century the treasury realised the profitability in the "petroleum" production and wanted to exploit this chance to reduce the foreign trade deficit, so it allocated 100,000 Hungarian crowns per annum for enhancing domestic production. The Hungarian Royal Geological Institute was appointed to provide scientific background for this effort. Sándor Wekerle prime minister wrote a letter to János Böckh, director of the Geological Institute (June 12, 1893.) and defined the expectations of the cabinet: "*… it is extremely important to extract mineral oil in our country. … I find it instrumental to drill deep wells for exploring the geological conditions ….*" After this date the Ministry of Finance issued exploration licenses and granted subsidies only upon receiving the expert opinion of the Institute, and the Institute had to perform technical oversight on the drilling of state-subsidised wells.

From Kissármás to Budafa 1909–1937

In 1909, next to Marosvásárhely at Kissármás (today: Sărmăşel, Romania), Kissármás–2 well was drilled for potash exploration The well had reached a high pressure gas reservoir at a depth of 302 m, whereupon the natural gas exploded upward with enormous energy — this was a turning point in the country's hydrocarbon exploration. Due to the discovery, significant drilling operations began in Transylvania. Between 1909 and 1918, 42 wells were drilled. 37 of these were successful, with 20–850 thousand m^3 daily gas production capacity. Reacting to the unexpected discovery, the government immediately recognised the underlying business opportunity and decided to make hydrocarbon exploration and production a state monopoly. The principles of crude oil and natural gas law were prepared, the Parliament enacted the draft law, and it

Figure 1.1. Baron Lorand Eötvös (1848–1919)

was published as the Act VI of 1911. Austria–Hungary was only the second country in the world to enact similar legislation. The act enabled domestic and international contractors to apply for and acquire exploration and production licenses (ŐSZ 2002). Oil exploration was not suspended during the 1st World War. At Nyitra county Egbell–I (today: Gbely, Slovakia) drilling of the gas well continued in 1914 and an oil reservoir was discovered. Hugó Böckh performed his first measure here in 1916 using the torsion balance developed by Baron Loránd Eötvös (Figure 1.1). The largest quantity of production in this area was in 1917, with 10,400 tons of crude oil produced (FÜLÖP 1984).

In 1917 Ferenc Pávai Vajna proved that faults in Dráva–Sava Valley extended to the Transdanubian part of Hungary, and in 1919 collaborated with Simon Papp to identify the Kiscsehi–Budafapuszta anticline structure. In the meantime, in 1918 hydrocarbon exploration was successful also in the Dráva–Sava Valley; at Bujavica (today Croatia) at 360 m depth natural gas and at 396 m depth crude oil was discovered.

Researchers supported by the Hungarian Treasury hoped to find oil and natural gas in the Miocene, Sarmatian–Pannonian aged strata of the Great Hungarian Plain. Implementing gravity measurements at Hortobágy and in the Debrecen region, the geological structures had been identified. Subsequent drilling exploration (Hajdúszoboszló, Debrecen, Karcag, Tiszaörs) revealed thermal water reservoirs with only traces of gas. At the same time, Jr. Lajos Lóczy was looking for oil in and gas in the south-western part of Transdanubia, and in the older (Palaeogene) strata of North-eastern Hungary. He had good reason to be optimistic, as east of Budapest 19 wells were drilled between 1912–1936 (Őrszentmiklós, Tard, Bogács). These revealed promising crude oil and natural gas traces, in addition to other traces found near the surface (for example near to Recsk village) (BÉRCZI 2002).

Following Loránd Eötvös's death in 1919, methodological research and continued exploration went on within the framework of the Loránd Eötvös Geophysical Institute. Beginning in 1921, after the now reduced Hungary had been

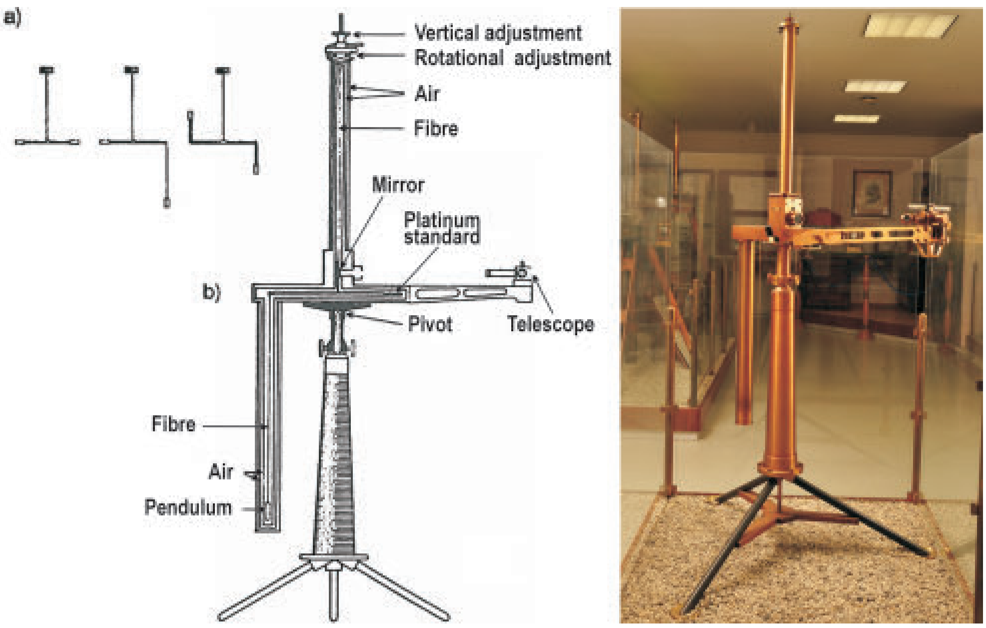


Figure 1.2. Internal structure of the Eötvös torsion balance
a) arm suspended on a torsion line and potential arrangement of weights b) general outlay drawing of Eötvös torsion balance (drawing: SIMONYI 2001)

deprived of many of its significant natural resources, exploration programs were launched within the country's new borders. These including oil exploration measurements in the Great Hungarian Plain, along with continuing efforts to modernise the Eötvös torsion balance. During the 1920s and 30s leading international oil exploration companies hired Hungarian experts for their projects in remote countries. Baron Loránd Eötvös designed an instrument (the Eötvös torsion balance) which revolutionised the oil sector (VERŐ 1996, Figure 1.2). Until the seismic exploration method was developed, the torsion balance had no competitor in the area of crude oil and natural gas exploration.

In November 1920, the D'Arcy Exploration Company Limited, a subsidiary of Anglo–Persian Oil Company Limited, founded an affiliate in Hungary named the Hungarian Oil Syndicate Ltd. This company acquired a 20-year concession for a 60,000 km^2 area. Using the Eötvös balance, a 10 gravity maximum was identified on the Great Hungarian Plain and deemed suitable for exploration projects. A total of three wells were drilled in Kiscsehi–Budafapuszta, Kurd and Baja. The kiscsehi–budafapuszta well missed the target field (later discovered) only by 300 m (on the surface). Over six years (1921–1926), three dry holes were drilled at a cost of 150,000 British Pounds, so the company left Hungary (Bérczi 2002).

In 1931, a crude oil cartel operating in the US state of Delaware established the European Gas and Electric Co, or Eurogasco. The company first discovered significant natural gas reservoirs in Vienna, then in 1933 concluded a concession agreement with the Hungarian State. They had already applied torsion balance measurements which they supplemented with seismic acquisitions, and magnetic measurements were also performed involving Hungarian experts. The company had introduced state-of-the-art rotary-type rigs into Hungary. These enabled cheaper, faster and more trouble-free deep drilling operations. The first three promising structures were discovered at Mihályi, Görgeteg and Inke. The Mihályi structure proved to contain carbon dioxide pure enough for food industry applications. In 1936 the first well was drilled at Budafapuszta. At 1754 m depth it produced gas with a strong gasoline odour, and continued producing 28,000 m^3 gas daily for nearly a year. Production started at the Budafa–2 well on November 21, 1937, producing 10,300 m^3 of natural gas and 65,000 m^3 of oil daily. Seven of the eight subsequent wells drilled in the area were also successful.

Table 1.1. Discovered domestic crude oil and natural gas fields 1935–37

Year	Fields
1935	Mihályi–Répcelak (carbon dioxide)
1936	Budafa, Inke, Őrszentmiklós
1937	Budafa–Kiscsehi, Budafa-deep, Bükkszék

During exploration in the Recsk region oil outflows were found at several locations. The Ministry of Industry ordered drilling in the dome at Bükkszék, where previous mapping surveys has indicated promising deposits, and on February 21, 1937 crude oil was discovered at a depth of 263 m, with production starting a few months later. This accumulation proved to be fairly small, and during the next 10 years 11,600 tons of oil was produced there. The Bükkszék–27 well also discovered mineral water, known as Salvus water, and a medicinal spa was built to use this water ressource.

At Budafa in 1937 crude oil production was 1.36 kilotons, in 1943 it was 838 kt; and between 1937 and 1945 the cumulative production was 3,820 kt. Gas production increased from 2 million m^3 in 1937 to 266 million m^3 by 1943 (Fülöp 1984). Table 1.1 shows the initial successful discoveries.

From the discovery of Budafa until the end of the Second World War, 1937–1945

The state amended its agreement with Eurogasco in 1938, when the American Standard Oil Company entered into the deal and the founded Hungarian–American Oil Ltd (MAORT) as a subsidiary of Standard Oil of New Jersey on July 18, 1938, with its headquarters in Budapest. Standard Oil held a 90% stake and the Hungarian Treasury had 10%. MAORT performed exploration projects, and the discovery at Budafa was followed with other reservoirs: in 1940 Lovászi, in 1941 Újfalu, and in 1942 Hahót–Pusztaszentlászló. The World War II changed the process and structure of exploration and production. USA and Hungary became enemies in December 1941, so MAORT's assets were taken over by the Hungarian Treasury.

In 1940 the Hungarian–German Mineral Oil Works Ltd (MANÁT) acquired an exploration licence for the south-eastern part of the Great Hungarian Plain, covering a contiguous area of 18,500 km^2. The war prevented development of the Tótkomlós and Körösszegapáti natural gas deposits and of the oil reservoirs discovered in the Mura Valley at Petesháza and Alsólendva. For that reason, starting in 1940, the country could be supplied only from oil production in the South Zala region (Budafa–Lispe–Lovászi). The 420 kilotons/year production then available could cover Hungary's total demands, with one-third of the production even available for export. In 1941 a pipeline was built between Bázakerettye and the Shell Refinery at Csepel, with a branch line to Pétfürdő and Almásfüzitő. In those days this was the longest hydrocarbon transmission pipeline in Europe.

MANÁT exploration experts could present 38 gravity maximum between 1941–1944, most of them using then state-of-the-art part seismic methods. Structures in the vicinity of Algyő, Battonya, Ferencszállás, Kismarja, Madaras, Pusztaföldvár, Tompa, Tótkomlós were identified. It was proven that traps could be expected with high probability in the exploration blocks on the Great Hungarian Plain in Upper Miocene Pannonian sediments containing crude oil and natural gas accumulations, similarly to structures were already well-known in the Transdanubia. This opened totally new perspectives for hydrocarbon exploration in south-eastern Great Plain. A total of 15 wells were drilled. Due to the inaccuracies of the contemporary seismic measurements, the fields were mistaken with a couple of hundred metres for the first drilling. The first successful exploratory wells were drilled later, in the second half of the 50s and the first half of the 60s. These were the most important fields for Hungarian crude oil and natural gas production well into the 2000s.

In 1942 the Hungarian–Italian Mineral Oil Co (MOLÁRT), a joint venture of Hungary and the AGIP company, was

Table 1.2. Discovered crude oil and natural gas fields in Hungary 1938–1945

Year	Fields
1940	Lovászi
1941	Tótkomlós, Újfalu
1942	Pusztaszentlászló (Hahót–Söjtör)
1943	Hahót–Ederics

founded with a 55–45% ownership ratio. AGIP started drilling deep wells under Hungarian supervision in the former Transcarpatia in the spring of 1943. Their exploration and production results repeated the successes of the turn of the century — a daily flowrate of a few m^3/day, with a rapidly declining yield after swabbing and pumping a dense oil inflow.

Crude oil production in Hungary reached 838 kilotons in 1943, most of this volume produced by the MAORT oil producing facilities in Zala county. The domestic oil industry suffered significant damages during the last phase of the Second World War. Rehabilitation began right after the fighting was over. The Hungarian (south Zala region) oil fields were bombed on June 30, 1944, and though major damages were caused, the operating facilities were not destroyed. The situation was much more dramatic in the processing facilities, as 80% of capacity was destroyed and non-operational by war's end. Table 1.2 presents a summary of successful discoveries made during the 1940s.

Post World War years until the establishment of the OKGT — 1946–1960

After the Second World War hydrocarbon exploration operations were performed by the Hungarian–Soviet Oil Ltd (Maszovol) on the Great Hungarian Plain, while after the nationalisation of MAORT the Transdanubian State Crude Oil Company (DÁK) continued its research in the Transdanubian area. The two companies merged in 1952 under the name Maszolaj Ltd, and at the end of 1954 was given fully Hungarian ownership. In 1957 the National Oil Trust was established (FÜLÖP 1984).

After the war ended only MAORT remained among the research companies.It returned to Hungarian oil and gas exploration and production, its operations however limited to the Transdanubian area. Although the geology of this region became increasingly better known; development was not without difficulties due to the emerging political struggle in the country. The role of the American oil industry in Hungary finally came to an end due to the conceptional MAORT lawsuit and nationalisation on 31 of December, 1949.

The German-owned MANÁT Ltd, which had previously been exploring the Great Hungarian Plain, was transferred to the Soviet Union under the armistice agreement with Hungary and the Potsdam Treaty. The Soviet party accepted the recommendation of its experts and founded a Hungarian–Soviet joint venture. The Hungarian–Soviet Crude Oil Co (Maszovol), founded in 1946, continued exploration in North and East Hungary where the programs had earlier been suspended due to the war.

The Maszovol exploration area was 40,008.5 km^2. This area includes the Trans-Tisza region, the southern part of the Danube–Tisza zone and the Bükkalja area, where the Hungarian Treasury, the Anglo–Persian Oil Co and the MANÁT Ltd Had earlier pursued exploration. During its three and a half year existence, and starting in 1946, Maszovol drilled 36 exploration wells. Its activities are shown by the following production data: in 1947, 154 tons of oil, 192 tons of condensate and 6.4 million m^3 natural gas; in 1948, 517 tons of oil, 89 tons of condensate and 6.0 million m^3 natural gas; in 1949, 2,278 tons of oil, 985 tons of condensate, and 34.5 million m^3 of natural gas (DOBAI 2014).

Systematic drilling exploration of domed structures identified by geophysical methods had started at Körösszegapáti (1946), but a serious accident (including a gas blowout) terminated what had been a promising field of exploration. Shortly afterwards, in 1947, the Bi–1 well drilled into the Biharnagybajom structure and showed indications of commercially recoverable crude oil. Nearly 50 wells were drilled, among them five wells which were producing for a longer time, with a total of nearly 100,000 tons of crude oil. The field was shut down at the end of the 1960s. Opportunities in north-eastern Hungary were steadily and positively assessed during this time. This was justified and supported by the oil fields discovered near Mezőkeresztes (1950), and later at Demjén (1954). In the first case Triassic and Eocene limestones and dolomites hold the crude oil. In the second case the productive reservoirs are in Oligocene sandstones, and the content is dense, high-viscosity crude oil with low gas content. From 1970 to 1980, this zone became an internationally recognised area for testing various in-situ combustion methods of production technology (BÉRCZI 2002).

Intensive exploration in the Transdanubian region resulted in overwhelming success in 1951: exploration of the Nagylengyel oil field began with the Nagylengyel–2 well. The successfully drilled wells increased production from 483,000 tons/year in 1948 to 1.2 million tons by 1955. The flowrate in some wells could reach 200 tons/day, but most of the oil had to be pumped up, which was very difficult due to its great depth and high viscosity. Forced production caused water influx in the wells. The so-called CO_2 injection method was developed and successfully applied during this production, made possible because of significant CO_2 gas which had been discovered in the deeper strata of the Budafa field.

The Nagyalföld Crude Oil Production Company was established in 1954 for performing production operations in the area of the Great Hungarian Plain. In 1955 the area of activity was expanded to the surroundings of Szolnok city.

When the Soviet Union withdrew from the Hungarian oil industry in 1954, the Hungarian–Soviet Oil Ltd (Maszolaj, a joint venture created in 1950) was terminated. Maszolaj's shares and assets distributed to 24 companies, the largest being

the Magyar Kőolaj Rt. (Hungarian Crude Oil Ltd). This structure brought small businesses together in a very loose and inefficient co-operative organization. As a result, the former Ministry of Heavy Industry followed the Western example by founding the National Oil Trust in January 1, 1957. This organisation re-united the entire domestic hydrocarbon industry.

In 1957 a further plan for oil and gas exploration was prepared based on the interpretation of recent geophysical measurements and the re-evaluation of previous data, but based on the original work hypothesis and exploration concept. Experts successfully increased the production of Zala oilfields by introducing new technologies and they devoted great efforts to research in the Great Plain region. In October 1958 the first significant oil and gas reservoir of the Great Plain was discovered at Pusztaföldvár, and in 1959 the Battonya and Hajdúszoboszló gas fields were found. These three discoveries had a major effect on the energy management of the country, and a national natural gas program was launched. Table 1.3 presents the summary of the discoveries made during this period.

Table 1.3. Discovered crude oil and natural gas fields in Hungary 1946–1959

Year	Fields
1946	Répcelak és Répcelak-kevert gáz
1947	Biharnagybajom, Vétyem
1948	Biharnagybajom, Vétyem
1949	Biharnagybajom, Újfalu
1950	Biharnagybajom, Nagylengyel
1951	Mezőkeresztes
1952	Kilimán, Mezőkeresztes, Újfalu
1953	Demjén-Nyugat, Inke, Mezőkeresztes, Nádudvar, Szolnok
1954	Buzsák, Demjén-Nyugat, Görgeteg-Babócsa, Nádudvar, Nagylengyel–Barabásszeg, Őrszentmiklós, Rákóczifalva, Túrkeve-Kelet
1955	Nádudvar
1956	Bajcsa, Demjén-Kelet, Nádudvar, Püspökladány, Szolnok–Hajtótanya, Törtel
1957	Furta, Görgeteg-Babócsa, Heresznye, Jászkarajenő, Kaba, Nádudvar, Nagykörös, Törtel
1958	Furta, Kisújszállás-K, Nagylengyel, Pusztaföldvár, Szandaszőllős
1959	Battonya, Hajdúszoboszló, Heresznye, Nagykőrös-Dél–Kecskemét, Szandaszőllős, Tompa, Vízvár

The OKGT (National Oil and Gas Trust) era — 1960–1991

On 1 of October, 1960, the gas business was integrated to create the National Oil and Gas Trust (OKGT). It embraced the entire Hungarian oil and gas industry, including the Danube Oil Company, which was also jointly established. During this period exploration projects continued in the Transdanubian region in the area around Nagylengyel, resulting in new oil reservoirs. Even so, the Great Plain gradually took over the leading role in oil and natural gas production.

During the 1960s crude oil exploration projects in the Kiskunság region shifted towards the Tisza river. In 1962 significant crude oil and natural gas reserves were discovered at Üllés, and then in 1964 at Szank, but progress was hampered by blowouts. This was one reason why drilling at the Algyő–1 well was delayed, though the geological structure was already identified through seismic acquisition in December 1964. Finally, work could begin in June 1965 (Dank 2016). At the same time, at the request of an agricultural co-operative, the Water Research Company started to drill a water well next to Szeged, in Tápé, more than 4 km from the OKGT drilling site. At that well there was an unexpected crude oil blow out on 7 of July, 1965, as the local crew was untrained in blowout management. Finally, oil exploration experts were able to kill the well. Since then, Algyő has proved itself to be Hungary's largest hydrocarbon field ever, as a result of crude oil and natural gas resources discovered in subsequent exploration. Ongoing exploration projects then allowed for more intense production in the Great Plain. Together with production from greater depth in the Transdanubian part of Hungary, rates of 2 million tons/year of crude oil and 6 billion m^3/year of natural gas were achieved.

As a result of the Algyő discovery, Hungary's

Table 1.4. Hydrocarbon exploration wells reaching 4500 m well depth

Settlement	Well ID	Spudded	Total vertical depth (m)
Makó	TXM.Makó.7	2006	6085.0
Hódmezővásárhely	Hód.I	1972	5842.5
Makó	TXM.Makó.6	2006	5692.3
Békés	Békés.2	1987	5500.0
Lovászi	L.II	1970	5400.5
Tiszaalpár	Alp.I	1986	5305.0
Budafapuszta	B.IX	1977	5265.5
Derecske	Der.I	1978	5205.0
Bárszentmihályfa	Bm.I	1975	5075.5
Makó	Makó.2	1974	5060.0
Inke	I.I	1981	5000.0
Sarkadkeresztúr	Sark.I	1976	4841.0
Gátér	Gátér.M.1	1987	4800.0
Sáránd	Sár.I	1983	4800.0
Gyékényes	Gyék.I	1979	4675.0
Doboz	Doboz.I	1981	4656.0
Bősárkány	Bö.1	1969	4517.0
Kerkáskápolna	Ká.1	1968	4510.0
Kiskunhalas	Kiha.I	1987	4500.0
Budafapuszta	B.V	1970	4500.0
Külsővat	Kvat.1	1966	4500.0

crude oil and natural gas production reached a historic peak in the 1970s and 1980s, followed by a decline. These significant discoveries launched further and systematic exploration programmes in the wider region around Algyő and the southern part of the Great Plain, which resulted in another series of discoveries. Those fields were smaller than at Algyő, but significant compared to hydrocarbon-geological conditions elsewhere in Hungary. These resources were then developed. Experts prepared new exploration concepts supported by modern and better-quality seismic and well geophysical tools, and better prospecting methods (KÉSMÁRKY 2002, POLCZ, BARÁTH 2003, BODOKI, POLCZ 2016).

Steadily rising international crude oil prices required deeper exploration of the existing hydrocarbon fields and frontier zones. Significant developments were required for drilling deeper wells, due to the extremely high geothermal gradient in the Pannonian Basin (Table 1.4).

The results proved on the one hand the existence of hydrocarbon-generating mature source rocks in the deeper section of the basins in Hungary; on the other hand, these results showed the need for applying a different technology for discovering hydrocarbon reservoirs at greater depth and in more complex geological structures than those found in strata closer to the surface.

Table 1.5. Discovered crude oil- and natural gas fields in Hungary 1960–1991

Year	Fields
1960	Ebes, Ebes-É, Görgeteg-Babócsa, Kaba-Észak, Mezőhegyes, Nagykörös–Kálmánhegy, Nagylengyel–Barabásszeg, Nagylengyel, Pusztaszőlős, Rém, Vétyem-Kelet, Zagyvarékas
1961	Battonya-Kelet/6002, Mezőhegyes, Nagykőrös-Dél-Kecskemét, Tarany, Vízvár
1962	Demjén–Pünkösdhegy, Demjén-Kelet, Ikervár, Nagylengyel, Szarvas, Tatárülés-Kunmadaras, Zagyvarékas-Észak
1963	Farmos, Fedémes, Ikervár, Iharosberény, Kisújszállás-K, Uraiújfalu, Üllés, Zalatárnok
1964	Belezna, Demjén-Kelet, Heresznye, Vése, Karcag(–Bucsa), Martfű-Észak, Mezőcsokonya, Nagyatád, Nagykörü-Ny, Ölbő, Soltvadkert, Szank, Szécsény, Tiszapüspöki, Turgony
1965	Algyő, Cegléd, Dorozsma, Mezőcsokonya CO_2, Nagykörü, Sávoly
1966	Belezna, Demjén-Kelet, Tázlár, Tótkomlós-DNy
1967	Ásotthalom, Demjén-Kelet, Kiskunhalas, Nagylengyel, Pásztori
1968	Csanádapáca, Kelebia-Észak, Nagylengyel-Szilvágy
1969	Fegyvernek, Ferencszállás, Kisújszállás-K, Kisújszállás-Ny, Öttömös
1970	Battonya-Kelet, Belezna-Dél, Bugac, Kelebia-Dél, Kelebia-Észak, Kisújszállás-Nyugat, Martfű-Észak, Ortaháza
1971	Belezna-Dél, Demjén-Kelet, Eperjehegyhát, Kaszaper-Dél, Kiskunhalas, Nagykörü, Nagylengyel-Szilvágy Dél, Öttömös, Sóshartyán
1972	Abony, Endrőd–I., Hajdúszoboszló, Kecel, Kisújszállás-Nyugat, Pusztamagyaród, Szeged-Móraváros, Tótkomlós-Kelet
1973	Ferencszállás Kelet – Kiszombor, Nagylengyel-Szilvágy Dél, Püspökladány
1974	Forráskút–Sándorfalva, Füzesgyarmat, Kiskunhalas, Kiskunhalas-ÉK-metamorf, Komádi, Makó (Makó–2), Mórahalom, Pusztaapáti
1975	Budafa–Oltárc, Csanádapáca, Endrőd–III/C, Harka, Kevermes, Kiskunhalas ÉK-mezozoos, Komádi, Ortaháza-Nyugat, Üllés-DK
1976	Darány, Endrőd–III., Eresztő, Komádi, Liszó, Nagybakónak, Pátró, Sarkadkeresztúr, Szank, Újszilvás
1977	Álmosd, Békés, Endrőd–III/C, Forráskút, Komádi, Köröstarcsa, Szank ÉNy
1978	Csesztreg, Endrőd-Észak, Forráskút, Jászszentlászló, Kaba-Dél, Kiskunmajsa Dél, Komádi, Mezősas, Ruzsa, Somogyudvarhely, Szank Nyugat, Zalakaros-Sávoly
1979	Álmosd–4, Barcs-Nyugat, Berettyószentmárton, Biharugra, Darány-Nyugat, Homokszentgyörgy, Kengyel, Kiskunhalas-Dél, Kismarja, Kunszentmárton, Mezőpeterd, Ruzsa, Zsana-Észak-gáztároló
1980	Biharkeresztes, Darány-Nyugat, Dévaványa, Eresztő, Martfű Dél, Ruzsa, Sávoly, Szeghalom, Vízvár-Észak
1981	Dévaványa, Doboz, Kadarkút, Kismarja, Kismarja-Dél, Körösladány, Mélykút-Északkelet, Mezőtúr, Szeghalom, Üllés
1982	Battonya-Észak, Földes-Nyugat, Jánoshalma, Jánoshalma-Dél, Martfű-É-CO_2, Martfű-Észak–II., Penészlek (határmenti), Soltvadkert-Kelet, Szarvas, Szeghalom-É, Tompa-Észak, Tótkomlós-Észak
1983	Barcs-Nyugat, Biharkeresztes, Demjén-Kelet, Jánoshalma, Kiskunhalas-É, Kiskunmajsa, Penészlek, Penészlek (határmenti), Sáránd, Somogysámson, Tét–3
1984	Barcs-Nyugat, Besenyszög, Demjén, Dévaványa, Forráskút, Földes-Kelet, Horvátkút, Kiskunmajsa, Komádi, Kömpöc, Martfű-É-CO_2, Mezősas, Örménykút, Ruzsa, Tét-5
1985	Ásothalom-Észak, Demjén–Pünkösdhegy, Földes-Nyugat, Kiskunhalas-Dél, Kokad, Martfű-É-CO_2, Martfű-Észak-II., Mezőpeterd, Mezősas, Ortaháza Kelet, Szeghalom-Észak-5, Tázlár-Észak, Végegyháza-Nyugat
1986	Bajánsenye, Celldömölk-ÉNy, Földes-Nyugat, Kömpöc, Mezősas, Sáránd-sekély, Tázlár-Észak, Tét–6, Törökszentmiklós, Törökszentmiklós-Dél
1987	Kengyel-Észak, Kokad, Mezőcsokonya-Nyugat, Nagykörü-Ny, Tázlár-Észak, Tiszagyenda, Túrkeve-Nyugat, Zsombó
1988	Dévaványa-Dél, Dorozsma, Ebes-É, Egyek, Nagybánhegyes, Sávoly-Délkelet, Szeghalom-Nyugat, Végegyháza-Nyugat, Zsana-Nyugat
1989	Dévaványa-Dél, Dorozsma, Hegyfalu, Karcag, Köröstarcsa, Magyarbánhegyes, Magyardombegyháza-DNy, Medgyesegyháza, Mihályi-Dél, Nagybánhegyes, Őriszentpéter-Dél, Pat, Sávoly-Kelet, Szentgyörgyvölgy, Túrkeve-Kelet, Zsana-Nyugat
1990	Furta–Zsáka, Kiskunhalas-ÉNy, Köröstarcsa, Mezőhegyes-Nyugat, Pálmonostora-DNy, Pusztaszentlászló-Kelet, Szolnok-Délnyugat, Tószeg
1991	Abony, Csanádalberti-Észak, Kömpöc-Dél, Mezősas-Nyugat, Öttömös-Nyugat, Pitvaros-Észak, Pusztaszentlászló-Kelet, Szolnok–III. (-É–2), Tótkomlós-Dél, Tura, Túrkeve-Nyugat

The Hódmezővásárhely–I deep well was designed to be 6,000 metres deep, and aimed at the Makó Trust deep zone. As a result of careful geophysical preparatory work, successful logging followed at 4,611 and 5,100 m with inverted emulsion fluid. At a depth of 5,100 m, 810 bar pressure and 191 °C temperature was measured; at 5,418 m, 850 bar pressure and 210–213 °C temperature were recorded. Hungary's deepest well reached 5,842.5 m, at which point the drilling rod broke (Dobai 2014).

During this period new, enhanced oil and gas recovery methods were introduced. They included: the thermal (underground combustion) production method used in the heavy crude oil in the Demjén oilfield; routine application of water injection (in Pusztaföldvár, Kiskunhalas, Szank fields); CO_2 injection in the Budafa–Lovászi, Kiskunhalas, Szank, and Tázlár fields; a two-sided water flooding method for production in oil reservoirs with a large gas cap in the Algyő field; nitrogen gas injection to boost pressure; a laboratory preparation/experimental and pilot project for miscible displacement method (Szeged-Móraváros field); small scale water injection with chemicals as a pilot project in the Algyő field; CO_2 injection technology and field-size application in the Nagylengyel field; combined-method preparation (Kiskundorozsma field); and production intensification in low permeability rock formations using horizontal wells (Bérczi 2002). Table 1.5 presents the fields discovered after 1960.

From the foundation of Mol Plc (1991) until today

In conformity with the World Bank's recommendation for gas distribution companies, machine manufacturing companies, and CO_2 production and marketing companies, drilling companies became independent in 1999. As of September 30, 1991, OKGT ceased to exist. As its legal successor the Mol Hungarian Oil and Gas Plc was founded, at that time as a 100% state-owned company, and in 1995 its privatisation was launched.

During the 1990s and 2000s international exploration companies also entered Hungary, with periodically varying numbers and successes. Pursuant to the amendment of the Act XLVIII of 1993 (Mining Law) in 2010, areas delineated for hydrocarbon exploration, appraisal and production qualify as "closed areas". Based on geological data available for such closed areas and on contractor's initiatives, the ministery is entitled to issue invitations for the concession bid round for the areas where — considering sensitivity and vulnerability test reports in conformity with the relevant laws — extraction of minerals and geothermal energy seems promising for purposes of energy generation. In 2017 the fifth bid round was organised for concessions. As a result of previous tenders both Mol Plc, the largest domestic contractor, and international contractors could acquire hydrocarbon exploration blocks.

Over the past period several publications have described hydrocarbon exploration and production operations in Hungary. The work written by Tomor (1962) summarised oil and gas discoveries on a scientific level. Later work by Völgyi (1985) presented a detailed description broken down to reservoir level. Kőrössy (1987; 1988; 1990a, b; 1992; 2004; 2005a, b; 2014) reported on the exploration results on a regional basis. Hungary's hydrocarbon potential was presented in the work by Juhász, Kummer (1997) and Kovács Zs. (2012), while the non-conventional potential was described by Kovács Zs. and Fancsik (2016). Stratigraphy of Hungary's geological formations was introduced, focusing on hydrocarbon geology, by Bérczi, Jámbor (1998). Somfai et al. (1998) prepared a detailed description on hydrocarbons from sedimentary geological aspects. Pápay (2003) presented the operations in hydrocarbon reservoirs with detailed domestic examples.

As documented in the records of Mining and Geological Institute of Hungary, 8,431 exploratory wells were drilled in Hungary in areas identified as hydrocarbon exploration targets (Figure 1.3). The total drilling length is 15,225 km. The number of measured 2D seismic profiles is 7,632, with a total length of 92,720 km covering all the potential exploration areas (Figure 1.4). Most of the acquisitions and measurements were performed by GES Kft. (operating within the oil industry) and, in some areas, the Hungarian State Eötvös Loránd Geophysical Institute (MÁELGI) (Késmárky 2002, Polcz, Baráth 2003, Bodoki, Polcz 2016). The number of the measured gravity points is 391,900, and magnetic field measurements were taken at 203,548 points, and magneto-telluric probes were made at 4,784 points. A vertical seismic profile (VSP) was taken at 398 exploration wells, and seismic-logging operations were implemented in 378 wells. As a result of exploration projects we can obtain better and better logs with higher resolution in the wells. The variety of well geophysical logs is also increasing. These days geophysical logs can provide very substantial and robust information regarding the sequence of geological strata crossed by the log, while the number and length of core samples has dropped to a minimum.

Ever more exploration areas are being analysed with 3D seismic reflexion measurements instead of 2D logs (Figure 1.5). The Kiskunhalas 3D was the first acquisition of this kind in 1990, at that time ordered by OKGT. Most of the acquisitions were later performed by GES Ltd a Mol Plc subsidiary, ordered by Mol Plc Until 2017, 123 areas with various extensions were explored. These were in part initiated by international companies operating in the relevant areas.

As a result of more than 100 years of exploration, today the State Mineral Resources and Geothermal Energy Reserve Registry has data on 1,451 reservoirs in 314 hydrocarbon fields. Figure 1.6 presents the exploration blocks with the discovered zones and fields. Table 1.6 presents the fields and the new field sections discovered since 1992.

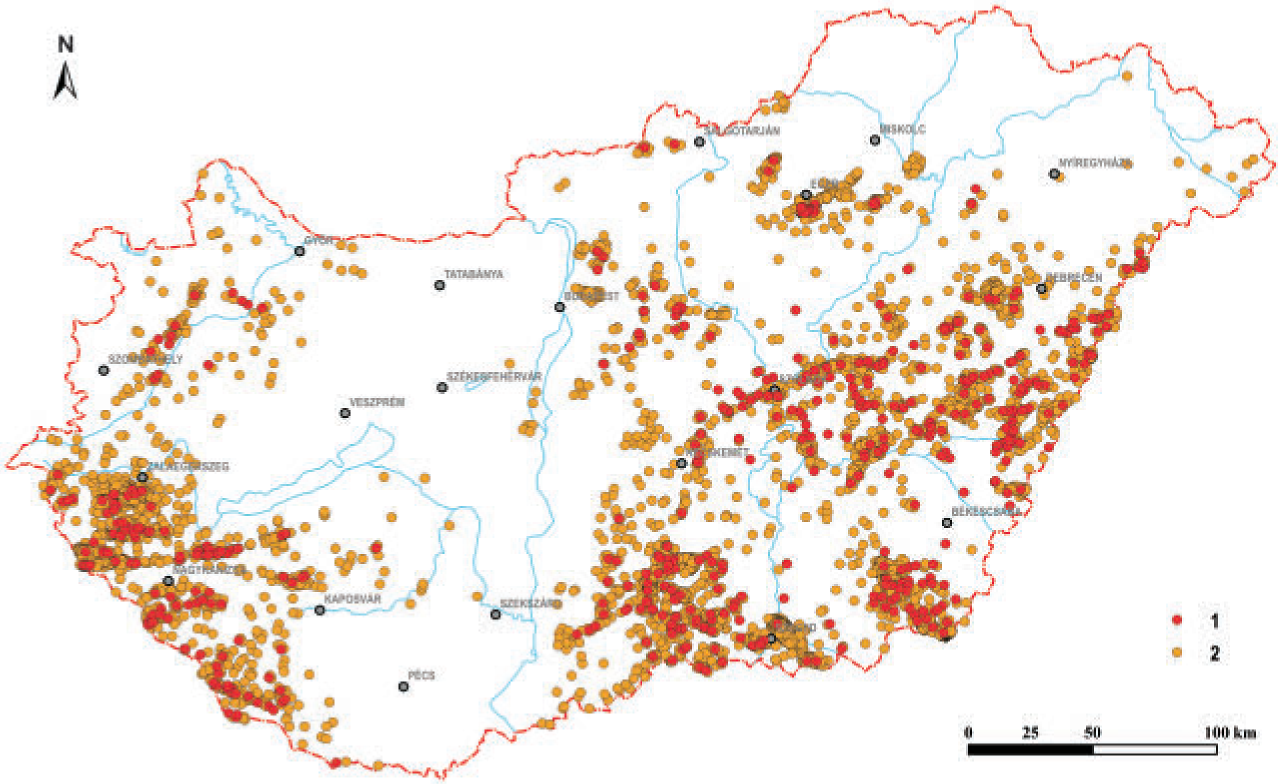


Figure 1.3. Hydrocarbon exploration and production wells drilled in Hungary until 2017
Legend: 1. field discovery well, 2. other hydrocarbon exploration or production wells

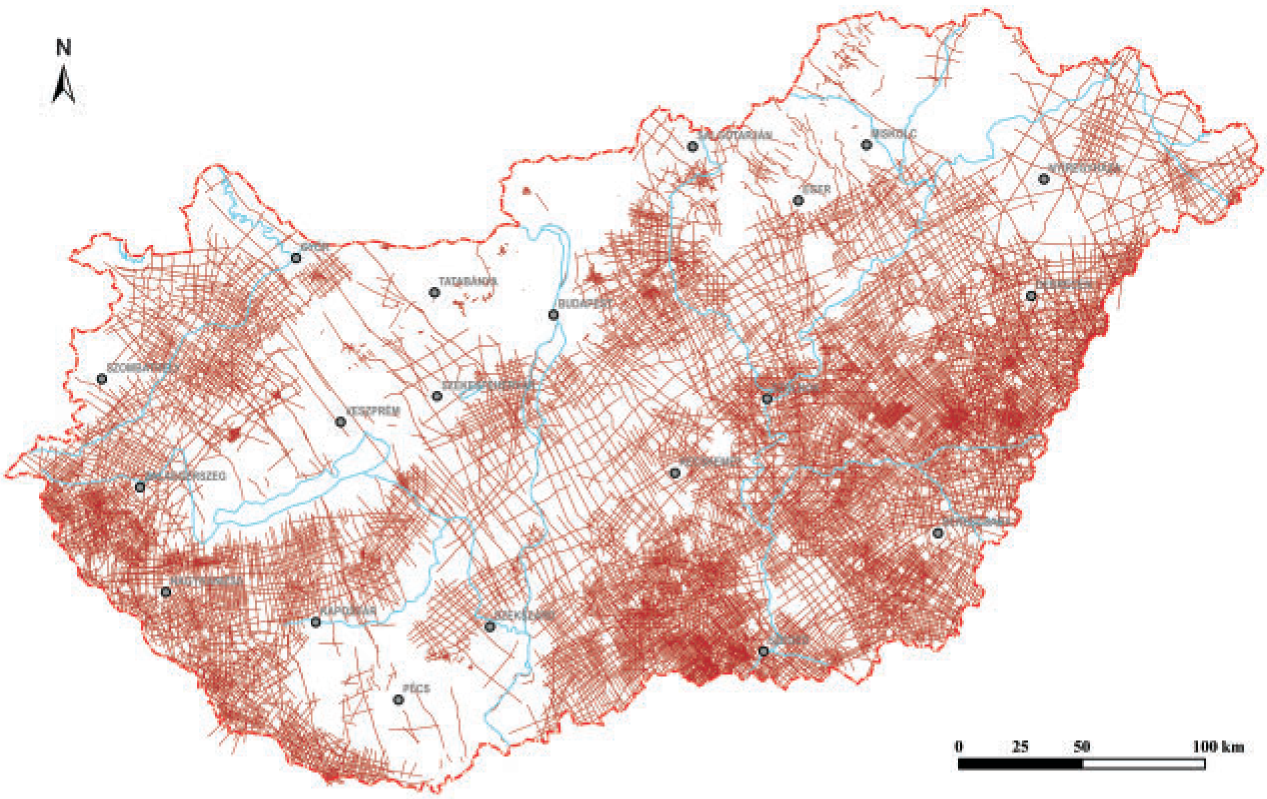


Figure 1.4. Trace lines of 2D seismic measurements in Hungary by 2017

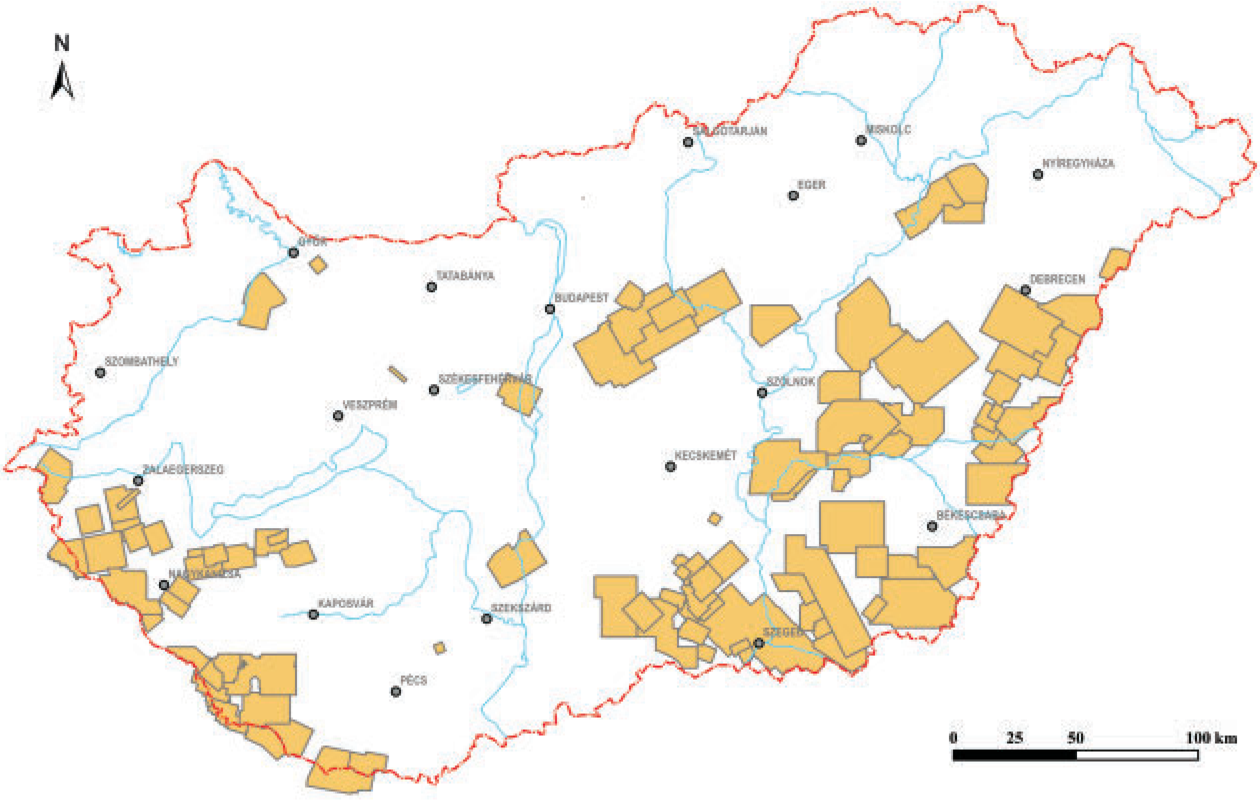


Figure 1.5. Areas covered by 3D seismic acquisitions in Hungary until 2017

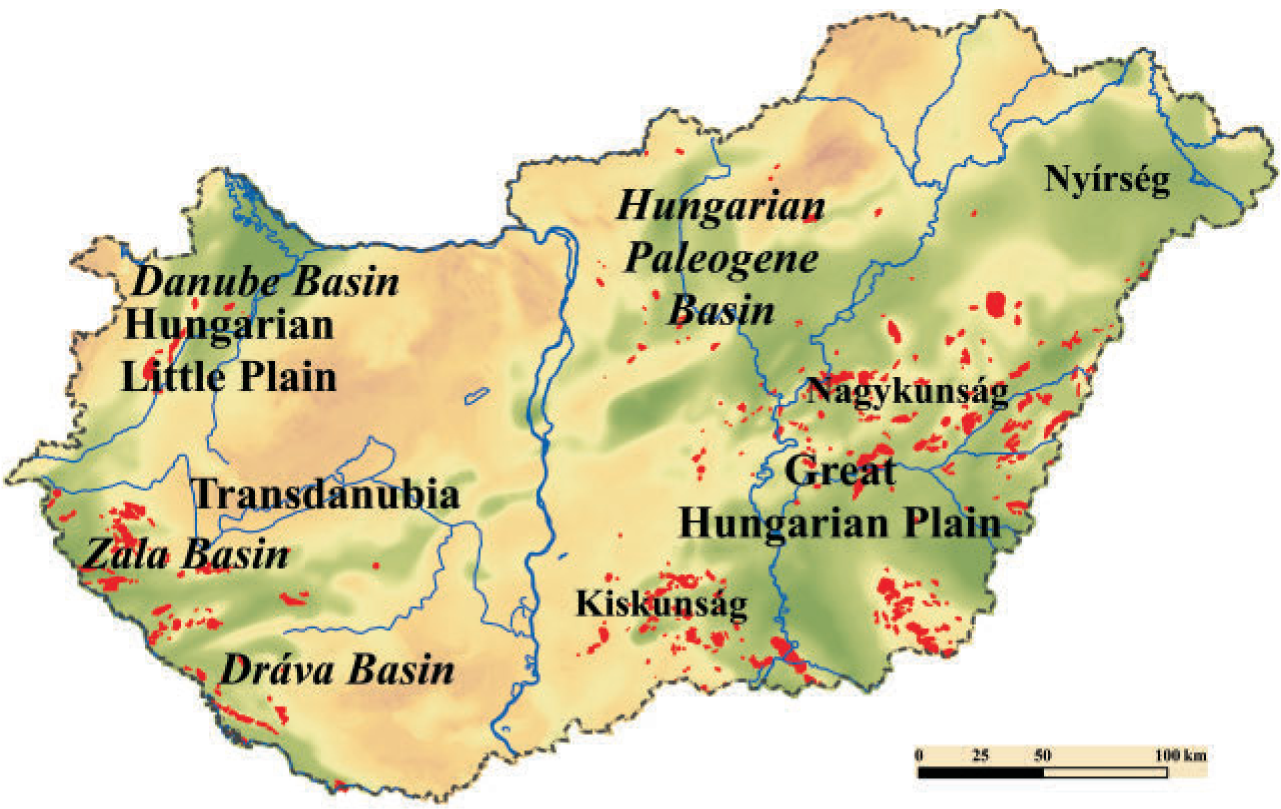


Figure 1.6. Discovered conventional crude oil and natural gas fields and the main exploration regions in Hungary
(fields are presented with red spots; green-shaded areas are the deep basins)

Table 1.6. Discovered crude oil and natural gas fields in Hungary1992–2014

Year	Fields
1992	Csanádalberti-Észak, Öttömös-Kelet, Öttömös-Ny/I.,III., Sávoly-Nyugat, Vízvár-Észak
1993	Mogyoród, Öttömös-Kelet, Öttömös-Nyugat/2002
1994	Dány, Nagybakónak
1995	Jankapuszta, Kismarja-Nyugat, Kisújszállás-ÉK, Sávoly-Délkelet
1996	Komádi, Medgyesbodzás, Mezősas-Nyugat, Nagykereki-Nyugat
1997	Csombárd, Monor-Észak, Sávoly-Dél
1998	Furta-Észak/6010, Sávoly-Dél, Sávoly-Délkelet-Kápolnapuszta, Sávoly-Délkelet-Szőcsénypuszta
1999	Csólyospálos-Kelet, Iharos-2, Monostorpályi-DK, Tóalmás-Dél, Zalakomár
2000	Szentmihálytelek
2001	Borota, Hosszúpályi-D, Monostorpályi-DK, Nagykáta, Szentgyörgyvölgy, Tóalmás-Dél-Szentmártonkáta, Tóalmás-Dél, Törökkoppány
2002	Tóalmás-Dél
2003	Gomba, Örményes-Délkelet, Pusztaföldvár-Észak, Túrkeve
2004	Berzence, Hosszúpályi-D, Örményes-Kelet
2006	Álmosd-Észak, Berettyóújfalu, Dévaványa, Gomba-Dél, Gomba-Észak, Kenderes-Dél, Kiskunhalas-15, Létavértes, Okány-1, Zaláta
2007	Kőrösújfalu I, Kőrösújfalu II, Nagykőrös-Dél, Zsadány-Észak, Öttömös
2008	Dévaványa-Kelet, Endrőd-Kelet, Zsáka, Hajdúnánás, Kőrösújfalu-II, Magyardombegyháza-DNy, Mindszent (unconventional gas), Okány-3, Örtilos, Sülysáp-Észak, Tatárvár, Tiszakécske, Túrkeve-Dél, Túrkeve-ÉK,
2009	Álmosd-Észak, Balotaszállás-Mély (unconventional gas), Barcs Mézes, Hódmezővásárhely (unconventional gas), Kunágota, Magyarbánhegyes-Kelet, Magyardombegyháza-DNy, Nyékpuszta, Nyékpuszta (unconventional gas), Ócsa, Szabadkígyós (unconventional gas), Túrkeve-Ény, Makó-árok-I. (unconventional gas, condensate)
2010	Berettyóújfalu (Beru-4) (unconventional gas), Kótpuszta, Kőrösújfalu-I, Magyarbánhegyes-Dél, Mezőhegyes, Mezőhegyes-DK, Penészlek, Tiszavasvári, Túrkeve-ÉNy
2011	Monostorpályi-K, Öcsöd, Tóalmás-Dél, Tófej, Túrkeve-ÉNy, Vésztő
2012	Belezna-Kelet-2, Gutorfölde, HHE-Jánosmajor-3, Nagykáta-Ny, Pély, Rádi-1, Tiszasziget-2
2013	Belezna-Kelet-1, Gyulavári (unconventional gas), Hajdúbagos-Kelet, Páhi
2014	Berettyószentmárton-Dél, Öcsöd

The quantity of crude oil produced from fields discovered by explorations today is more than 100 million tons, and the combustible natural gas production is higher than 235 billion m^3. Figure 1.7 presents the cumulative production over the past 40 years. The annual production data show a declining trend in the past decades (KOVÁCS Zs. 2016, Figure 1.8). The first reason for that is the decreasing number of exploration wells, something that could not be offset either through a higher number of modern 3D seismic measurements, improved prospecting methods, or the application of enhanced and effective production methods. The other reason is that most of the reservoir structures that can be easily identified with the applied geology concepts and geophysical exploration methods have already been discovered. The international petroleum industry qualifies Hungary's territory as a so-called "mature hydrocarbon region." Experts are aware of the geological structure of the evolutionary process and geological structure of the reservoirs. As a result, the routine application of standard exploration concepts are not likely to produce significant new discoveries.

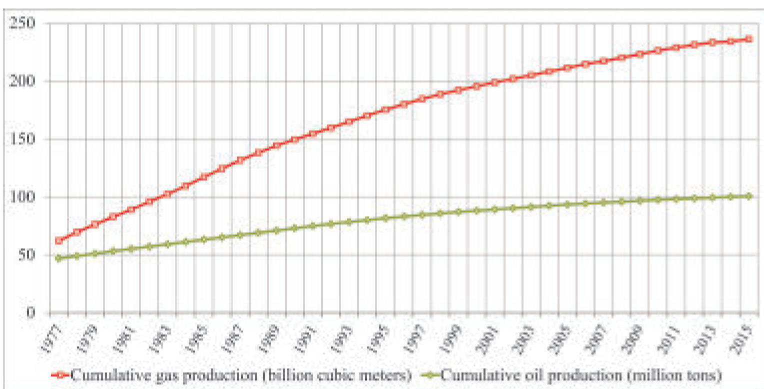


Figure 1.7. Cumulative crude oil and natural gas production since 1977

At present Hungary needs natural gas and crude oil imports. Declining production is offset by reducing residential consumption, which has been dropped from 14 billion m^3 to nearly 8 BCM, and the country's relatively large storage capacity (Hungary has 6.2 BCM of underground gas storage capacity).

Work going on in some under-explored

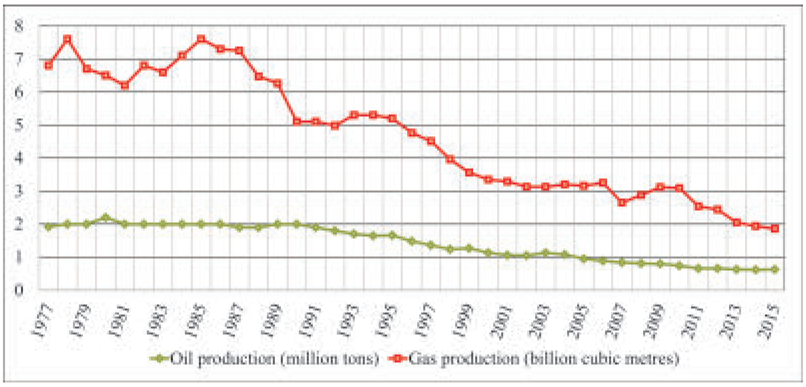


Figure 1.8. Tendency of annually produced hydrocarbons in the past four decades

regions are quite promising as regards conventional hydrocarbon exploration. These regions include certain parts of Kisalföld, Nyírség, Kiskunság, some part of the Dráva Basin and the Palaeogene Basin. Exploration of the pre-Pannonian Miocene formations, and the sediments containing thick embedded layers of volcanic or tuff origin, as in Nyírség — are quite promising. Planned exploration of shallow biogenic methane gas reserves in Pannonian strata also shows promise. In Hungary there are favourable chances for the exploration of so-called unconventional hydrocarbons — the already known and hoped resources may be significantly higher than the conventional hydrocarbon resources discovered so far. A separate chapter in this document addresses that topic. Some of the residual reserve left behind in the matured producing fields as recoverable resource, formerly deemed as unrecoverable, can now be extracted using modern production processes. Finally, a combustible part of natural gas with high CO_2 and nitrogen content might yet become a significant source of energy if the inert portion can be separated.

Domestic crude oil and natural gas production is very important, and based on natural capacities we may justifiably hope for further as yet undiscovered resources. Fortunately, Hungary has the properly qualified manpower, geologican and hydrocarbon experts, as well as the necessary infrastructure. There is still a possibility that new, successful exploration results may offset the depletion of discovered reserves and increasing import dependency. Assuming long term, successful exploration activity, technology development and the successful development of unconventional hydrocarbon resources, the hydrocarbon-production downturn might yet be be slowed and maybe even reversed.

Geology of Hungary — an introduction to the geology of sub-basins

Tamás Budai, Gyula Maros

2

The position of the Pannonian Basin in the Alpine orogenic system

The Alpine orogenic system (Figure 2.1) was formed by the collision of the stable European Platform and the Adriatic microplate of the African Plate (Argand 1924, Channell, Horváth 1976). Subduction of the oceanic branches left behind complex suture zones, nappe systems, numerous crustal blocks and several oceanic crust fragments from the formation of the Alpine–Carpathian–Dinaridic system. Microplates were broken off the continental plates, and their movements were characterised by different rotations and extrusions. The polarity of the nappe systems along the suture zones was turned to the opposite direction, and the obducted continental crust slabs appear either in the lower crust or the upper crust (Handy et al. 2014). This complex evolution created a varied structural pattern and sedimentary environment in the region. The crust-mantle detachment (Handy et al. 2014) and upwelling of the asthenosphere (Horváth et al. 2007) led to the formation of the Pannonian Basin, one of the Earth's best-investigated intramountain basins.

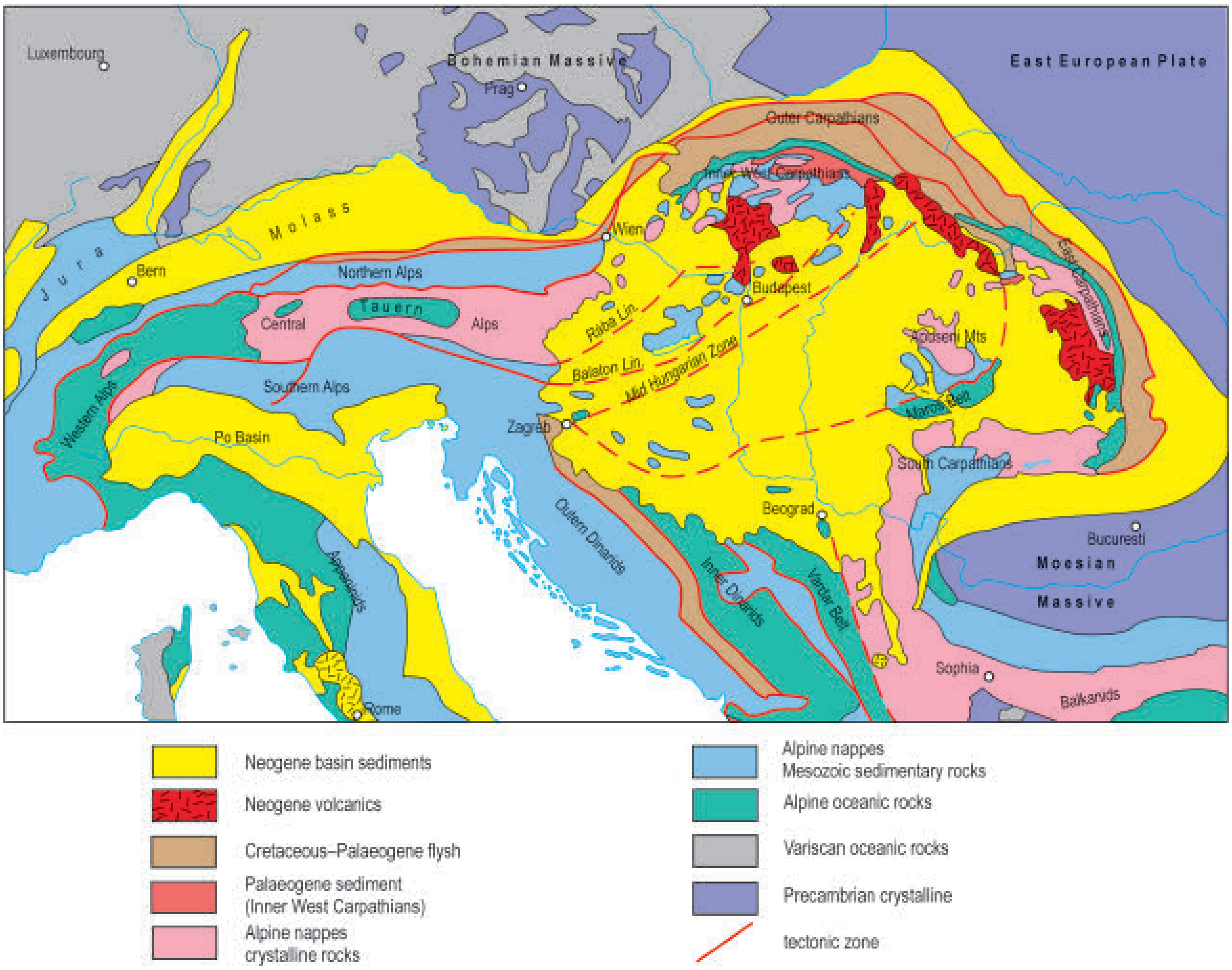


Figure 2.1. Tectonic position of the Pannonian Basin within the Mediterranean region (after Horváth in Haas [ed.] 2002)

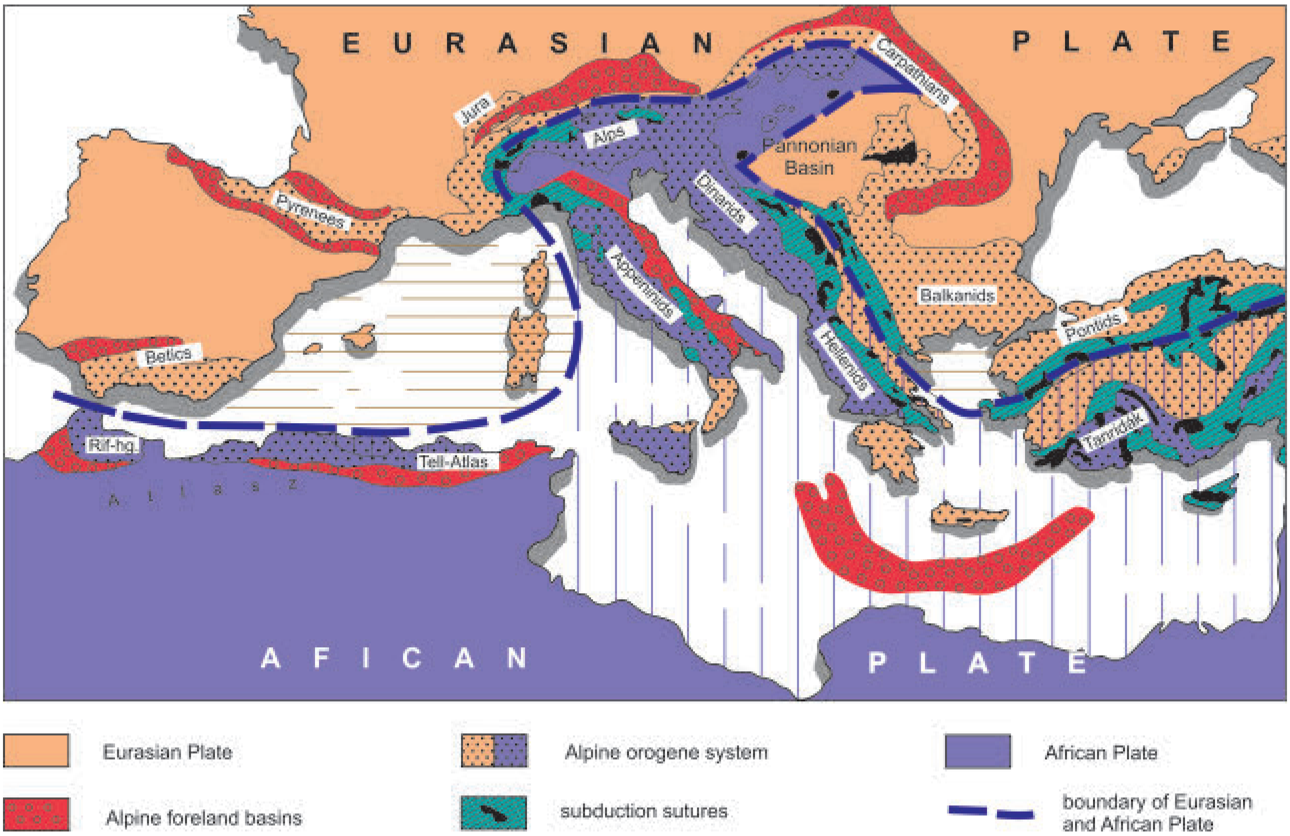


Figure 2.2. Geotectonic position of the Carpathian basin within the Alp–Carpathian-Dinaride system (after HAAS et al. 2002)

The present area of Hungary stretches across the Carpathian Basin and is surrounded by the mountain chains of the Alps–Carpathians–Dinarides. It is a relatively young intramountain basin, although with a highly complex geological setting (Figure 2.2). The Pannonian Basin itself, apart from the Vienna and Transylvanian basins, is a geologically well defined structure. Its sub-basins are the Kisalföld (Little Hungarian Plain or Danube Basin), the Steier Basin, the Dráva Trench, the Eastern Slovakian Basin, and the Alföld (Great Hungarian Plain), together with the areas of Bácska, Bánát and Kárpátalja (Transcarpathia). The basement of the basin is built up by pre-Cenozoic rock units which are exclusively exposed on the surface in the Sopron–Kőszeg, Transdanubian Range, Bükk, Aggtelek–Rudabánya, Mecsek and Villány mountain ranges. The Pannonian Basin is covered by younger Cenozoic sediments locally even thousand metres in the plains and hills.

Geology of the basement

The pre-Cenozoic basement of the Carpathian Basin is composed by two different lithospheric mega-units with different geological features (Figure 2.3). The Alcapa Mega-unit has a highly complex geologic setup and originated from the African Plate, while the nowadays south-situated Tisza Mega-unit has a European Plate origin. The two tectonic mega-units are attached to each other along the Mid-Hungarian Shear Zone which stretches SW to NE. The Mid-Transdanubian (Sava) Unit, situated south of the Mid-Hungarian Line (or Lineament), has two definitions in the most recent literature: according to HAAS et al. (2000), it is defined as a highly deformed geologic unit with Southern Alpine origin, but excluding the Szolnok–Máramaros flysch belt (Figure 2.4). SCHMID et al. (2008) and USTASZEWSKY et al. (2008) have a different opinion, as they include the Szolnok–Máramaros flysch belt in the Sava Unit. The geological framework presented here follows the work of HAAS et al. (2000).

The basement of Transdanubia is built up from the tectonic units of the Austroalpine Nappe System which stretches to Western Hungary. Metamorphic Jurassic phyllites of the Penninic Unit are exposed in a window below the Austroalpine Nappes. Palaeozoic gneiss and schists of the Lower Austroalpine Nappes are exposed in the Sopron Mountains and its surroundings. The slightly metamorphosed shales, sandstones and gabbros of the Palaeozoic basement of the Danube Basin are the direct extensions of the Upper Austroalpine Nappes.

The Transdanubian Range Unit has the uppermost tectonic position within the Austroalpine Nappe System, which consists of mostly non-metamorphosed rocks (TARI 1994). The only exception is the Variscian basement of the unit, with

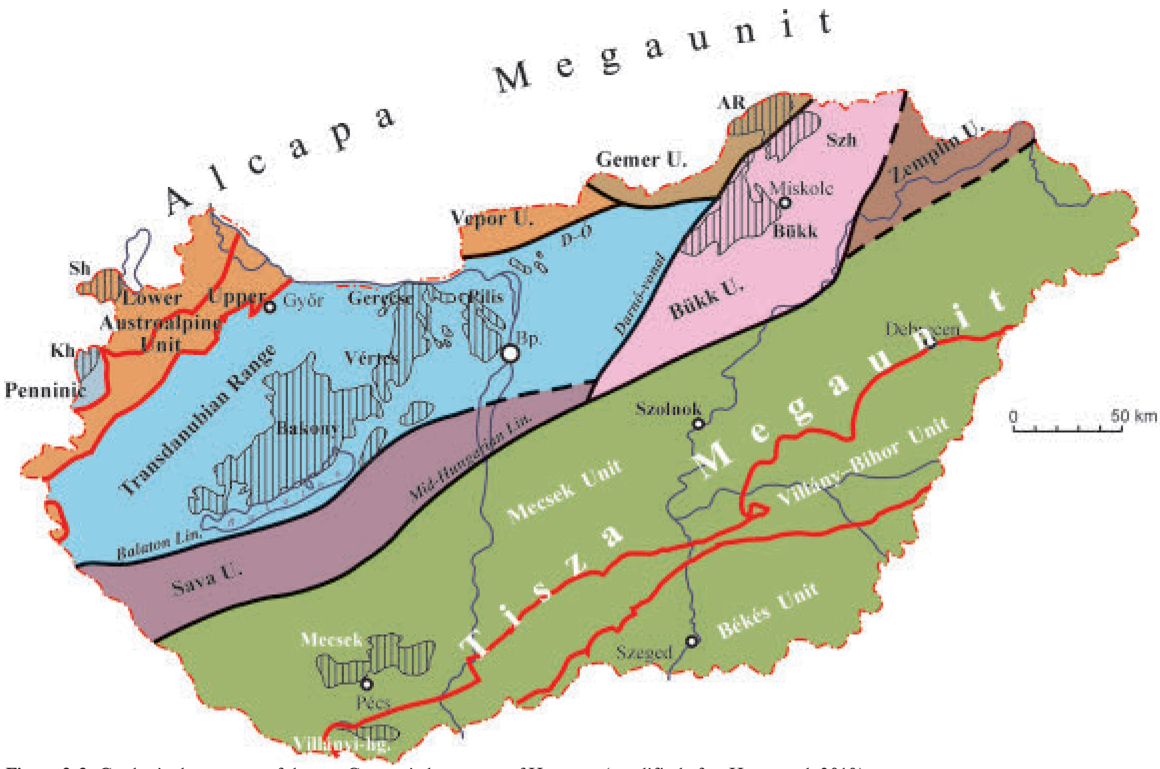


Figure 2.3. Geological structure of the pre-Cenozoic basement of Hungary (modified after HAAS et al. 2010)
Red lines represent nappe boundaries, while black ones are the boundaries of Cenozoic structures. AR – Aggtelek–Rudabánya Unit, D–Ó – Diósjenő–Ógyalla Line, Kh – Kőszeg Mountains, Sh – Sopron Mountains, Szh – Szendrő Mountains

granite intrusions along the Balaton Line which are exposed on the surface in the Velence Mountains. After a gap, the Variscian basement is covered with alluvial and shallow marine Upper Permian molasses, which was followed by a marine Triassic, mainly shallow water carbonates and fine-grained siliciclastic sediments in great, 2,500–3,000 metres thickness. The thickness of the Jurassic – Lower Cretaceous marine sediments may vary, but is mostly characterised by limestones and, in the Gerecse Mountains, siliciclastic deposits. The Upper Cretaceous sequence, dominated by marl- and shallow water carbonate, extends SW–NE in a syncline formed during the middle Cretaceous, and deposited (after a huge gap) onto the older rock basement surface.

The Transdanubian Range on its northern margin is attached along the Diósjenő–Ógyalla Line to the Vepor–Gömör Unit of Inner Carpathian affinity.

The first is characterised by metamorphic schists and gneisses, the latter is built mostly of Triassic carbonates which are

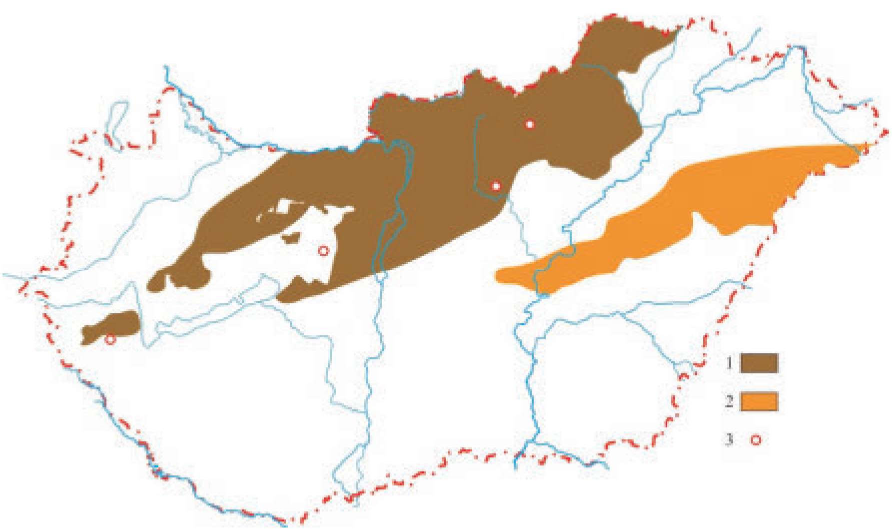


Figure 2.4. Extension of Palaeogene formations of Hungary (after NAGYMAROSY, in HAAS et al. 2001)
1. epicontinental deposits, 2. Szolnok flysch, 3. volcanic centers

very thick (2,000–3,000 metres), and exposed in the Aggtelek–Rudabánya Unit. Both have a relatively lesser amount of Jurassic or siliciclastic deposits.

The Mid Hungarian Mega-unit (or Shear Zone) is divided into the Sava and Bükk Units, and has a rather complex heterogenic structure due to the shear tectonics between the Alcapa and Tisza Mega-units. Its NW border of the zone is composed of the Balaton, Tóalmás and Darnó lines; its SE margin is the Kapos–Tamási–Kulcs Line. The pre-Cenozoic basement of the mega-unit has an outcropping in the Szendrő and Uppony Mountains, as well as in the Bükk area. The Szendrő–Uppony Mountains are built by slightly metamorphosed Palaeozoic siliciclastic rocks. Most of the Bükk is made of Permian–Triassic carbonates, and Jurassic igneous and siliciclastic rocks. The basement of the Sava Unit, the SW part of the Mid Hungarian Mega-unit, is composed of shallow marine and terrestrial Permian sequences and by Triassic carbonate formations.

The Mesozoic nappe system of the basement of the Tisza Mega-unit is exposed in the Mecsek and Villány Mountains. Its pre-Alpine basement is composed mostly of poly-metamorphic rocks such as schist, gneiss and amphibolite, with some granites occurring. The massive, several-thousand metre thick Carboniferous, Permian and Lower Triassic terrestrial sedimentary sequence is overlain by Middle Triassic shallow marine carbonates and Upper Triassic – Lower Jurassic siliciclastic rocks. The Middle Jurassic and the Lower Cretaceous series are characterised mostly by deep marine carbonates with volcanics in the Lower Cretaceous. Nappes of the mega-unit were formed as a result of Eoalpine movements during the the mid-Cretaceous. Their elevated erosional surface is covered by Upper Cretaceous marly sequence with a huge gap.

The metamorphosed basement of the Zemplén Unit is composed of schists and gneiss, followed by a massive, approximately 2000 metres thick Carboniferous, Permian and Triassic sequence.

According to most recent syntheses (SCHMID et al. 2004, 2008; USTASZEWSKI et al. 2008), the highly deformed zone of the Mid-Hungarian Mega-unit can be divided into two parts. One of the subunits has Southern Alpine origin and is considered more or less equal to the Sava Unit of HAAS et al. (2000), while the other one has an oceanic crust of reduced thickness towards SW and is covered by marine sediments. This second subunit is deformed in an S-shape and continues along the Mid-Hungarian Mega-unit to the Máramaros Flysch Belt. The above mentioned authors call this S-shape zone the Sava Zone, because it is partly follows the valley of River Sava, and they define it as a Palaeogene suture zone between the Tisza–Dacia Mega-units and the Dinarides (Figure 2.4).

Cenozoic formations

This sub-chapter follows the works of HAAS et al. (2001, 2012) in its geologic description of rocks deposited above the pre-Cenozoic basement as basin filling sediments.

Palaeogene

In the Tisza Mega-unit there are no traces of Eocene and Oligocene rocks, apart from the Szolnok Flysch. In contrast, several areas in the Transdanubian Range and the Bükk Mountains (Figure 2.4) have very thick Palaeogene sediments. These are Eocene limestones and marls, and Oligocene marine and terrestrial siliciclastic rocks such as conglomerates, sandstones, aleurolites and clays. Palaeogene sedimentary units are intercalated with volcanites in the Zala Basin, in the vicinity of the Velence Mountains and in the northern foreland of the Mátra Mountains.

Neogene

The Hungarian Neogene is characterised by the formation, evolution and infilling of the Pannonian Basin, which was a sub-basin of the former Paratethys over the last 24 million years. During this time, within the Intra-Carpathian region, 6000–7000 m deep sub-basins and ridges were formed. These were infilled with fine grained siliciclastic sediments that were transported from the continuously emerging areas of Alps and Carpathians.

Early Miocene

At the beginning of the Miocene, marine sedimentation was limited to the northern sub-basins of the Palaeogene Basin. The fine grained open marine sedimentation was characteristic of the Late Oligocene, but this situation changed with the deposition of coarser grained material in the Early Miocene, supplied by newly formed huge delta systems. The continuous infilling of the basin was covered by very thick layers of riolite tuffs. After and during the Ottnangian, coal deposition occurred in many areas of the evolving lacustrine and swamp environments. Simultaneously, thick deposits of fluvial sediments were deposited in the Tisza Mega-unit , and in the freshwater marshes on the alluvial plains. The intense andesite volcanism during the Early Miocene was related to the beginning of the subduction of the Magura Ocean.

At the beginning of the Karpatian, due to narrowed sea pathways, a brackish water environment came about in the region of the present Alpokalja and Mecsek Mountains, and in the northern areas. As the sea level rose, fine-grained siliciclastic sequences were deposited in the open basins. At the end of the Karpatian coarse-grained and carbonate sedimentation took place again due as the sea became shallower.

Middle Miocene

In the Badenian age of the Middle Miocene, pelagic basins were formed in the trenches opened up in the Karpatian, where fine-grained siliciclastic sediments were deposited. Due to the continuous subduction of the European Plate, an intensive, island arc-type andesite volcanism took place during the mid-Badenian, and a chain of great volcanoes were formed along the inner arc of the emerging Carpathians. During the sea-level rise in the late Badenian, carbonate sedimentation took place in shallow marine shelf environments, while sedimentation was characterised by fine-grained siliciclastic deposits in the deep marine environments.

In the Middle Miocene, at the beginning of the Sarmatian, volcanic activity renewed with riolitic tuff falls, followed by carbonate sedimentation in shallow marine shelf environments. The volcanism, predominantly felsic, andesite, riolite and dacite, moved eastward along the inner arc of the Carpathians, to the Tokaj–Nyírség area. There it formed huge stratovolcanoes.

Late Miocene

Evolution of the Carpathian Basin during the Late Miocene was determined by thermal subsidence, in contrast to the Middle Miocene extensional tectonics. In accordance with the changing tectonic regimes, sedimentation patterns also changed. By the beginning of the Middle Miocene the central basin of the former Paratethys had closed completely, forming a lake with no runoff. This was Lake Pannon, which gradually became a freshwater lake due to continuous river inflow.

Lake Pannon was accomplished by the sediment influx of rivers originating in the elevating areas of the Alps and Carpathians. The intense NW sediment input (from Sarmatian delta systems at the edge of the Danube Basin). Later, there was NE input from the Eastern Carpathians, as well as from the Dráva and Mura valleys. Delta systems started to develop on the coastal areas of the basin, then gradually. The water might have been a thousand metres deep in the deep inner areas, due to continuous subsidence in the Békés Trough. During the transgression, a calcareous marl with high organic content was deposited onto the top of the basement; while in the deeper central areas of the basin the sedimentary environment was characterised by very thick turbidites.

On the delta plain and at the delta front, there were various lithologies dominated by clay-silt sedimentation with sandstone interbeddings; on the delta slope, claymarl and silt was deposited.

The evolution of the Lake Pannon can be divided into three main phases. At the end of the Sarmatian, the Carpathian Basin was separated from the Paratethys, erosion started on the emerging areas near shore, and freshwater input increased. The second phase occurred during the continuous rise of the sea-level, when the lake filled the whole Carpathian Basin. The third phase occurred during a slow regression and infilling of the basin, which was terminated at the beginning of the Pliocene in the area of present-day Hungary.

Contemporaneously with the infilling of the deep basin, various depositional environments evolved in the shallow littoral areas. The southern forelands of the Transdanubian Range and the Alpokalja were characterised by shore swamps with lignite deposits. Sand and gravel deposited along the sea shore areas was characterised by strong wave activity, while still-water lagoons were characterised by the deposition of silt and clay, or by freshwater lime-mud. At the fronts of prograding deltas, sand was deposited, while the delta plain was characterised by fine grained sediment.

Felsic rhyolite volcanism continued on the northern margin of Pannonian Basin during the Late Miocene, and the Nyírség area and Tokaj Mountains were involved in its post-volcanic activity. Meanwhile, basaltic volcanism was active in the SW part of the Transdanubian Range and the Danube Basin .

Pliocene

The Pannonian Basin was almost completely filled with sediments by the beginning of the Pliocene, and a low dry-land emerged. In the subsiding areas, thick fluvial sedimentation occurred. At the shores of the basin mostly fine grained, fluvial-lacustrine siliciclastic sedimentation took place, while at the forelands of mountainous regions and hillsides coarser-grained sedimentation occurred. The Pliocene epoch was the main period of mafic basaltic volcanism, in the area from the Balaton Highland to the Danube Basin.

Quaternary

In the basinal areas (Danube Basin, Dráva Basin, Great Hungarian Plain) several-hundred metre thick fluvial sequences were deposited during the Quaternary, containing upward fining cycles of pebble, sand and clay beds.

In the Pleistocene ice-age, the Carpathian Basin was a periglacial area. During glacial periods, wind erosion was strong. Sand was blown from deflational areas and flood plains of the palaeo-Danube, and was deposited as blown sand. Thick loess was formed by deposition of wind-blown dust. In mountain areas the most widespread quaternary sediments are the slope deposits, while talus cones were formed at steeper hillsides.

River valleys were filled with alluvial deposits and accompanied by multi-levelled terraces on the sides. On the slopes of mountains that are built up of carbonates (such as the Gerecse, Buda Hills, Mecsek and Bükk Mountains) very thick travertine bodies were formed.

Holocene sediments are relatively limited in thickness. Rivers deposited fine-grained sediments (silt, clay) on their flood

plains and coarser grained sediments (gravel, sand) in their channels. Lacustrine environments were characterised by mud deposition, and swamps by peat accumulation.

Geodynamic model and evolution of the Pannonian Basin

From the basin evolution point of view, the geodynamic and plate tectonic model of the Pannonian Basin can be divided into two different phases of different durations. The first, longer period prior to the Pannonian Basin evolution (Pre-Pannonian) evolved during the Alpine cycle. It started in the Middle Permian and terminated in the Early Miocene. This was followed by a shorter phase of the Pannonian Basin's evolution, which lasted until recently.

Pre-Pannonian period of the Alpine cycle

By the end of the Carboniferous, a vast ocean called the Palaeotethys penetrated the Pangea supercontinent from the east. At its southern margin, a new ocean called the Neotethys opened up (RICOU 1994), starting from the middle of the Permian. During the formation of this new oceanic branch, a microcontinent named Kimmeria was cut off from the African Plate (STAMPFLI, BOREL 2004), and drifted towards the Eurasian Plate due to the widening of the new ocean. This resulted in the closure of the Palaeotethys ocean and the start of the so-called Cimmerian orogeny in the Late Jurassic. The Meliata–Vardar oceanic sub-branch was situated in the northern part of the Neotethys, where sequences of the Alcapa Mega-unit were deposited during the Triassic.

The other cardinal point of the tectonic evolution was the rifting of the Central Atlantic Ocean, which started in the Late Triassic. During this long process, more and more oceanic sub-basins were opened up and developed from the west. They are known as the Alpine Tethys (STAMPFLI, BOREL 2002). The Tisza Mega-unit was isolated from the European Plate during this process in the Middle Jurassic (CSONTOS, VÖRÖS 2004), and it was surrounded by the Meliata Ocean from the south and the Alpine Tethys from the north.

Features of sedimentary basins of different mega-units situated in different environments in the Triassic show more similarity in the Late Jurassic (GÉCZY 1973).

Closure of the Alpine Tethys started in the Early Cretaceous, nappe systems of the Austroalpine in the Alcapa Mega-unit (RATSCHBACHER et al. 1991), while in the Tisza Mega-unit the Mecsek, Villány–Bihor and Békés–Codru nappes were thrusted during the coeval shortening.

In the Transdanubian Range Unit only light flexural structures can be observed. In contrast, in other units of Alcapa Mega-unit, as well as in the Tisza Mega-unit (KOVÁCS S. et al. 2000), fold tectonics were more intensive during these processes. The deeply buried nappes were highly metamorphosed and suffered plastic deformations. Variscian crystalline rocks in the basement of different units suffered retrograde Alpine metamorphism (HAAS ed. 2001).

The compressional phase was followed by quite rapid emergence and gravitational collapse starting in the Late Cretaceous. This is the so-called “Gosau event,” which resulted in a deposition of terrestrial, terrigenous, reef, and later a continuously deepening marine sequence above the folded and erosionally truncated surface of the Alcapa Mega-unit. The chain of Gosau basins were surrounded by normal and strike-slip faults. Due to the north–south compression, the emerging nappe systems were deformed by transpressional stress fields (FROIZHEIM et al.2008).

During the Palaeogene, the Hungarian Palaeogene Basin was formed (BÁLDI 1986), and stretched from Slovenia to the present Northern Hungary. From the plate tectonic point of view, it was a foreland, flexural-type basin (TARI et al. 1993), subsidence of which was provoked by the load of the nappe stacks buckling the continental crust.

The Alcapa Mega-unit, contemporaneously with the formation of the Palaeogene Basin, was moving towards the ENE along the Periadriatic Lineament and the Balaton Line of the Mid-Hungarian Shear Zone (KÁZMÉR, KOVÁCS S. 1985).

The geodynamic model of this movement can be explained as an escaping orogenic wedge, or as a gravitational collapse along with a dragging effect associated with the initial subduction beneath the Eastern Carpathians. Most likely, both effects were involved.

Palaeogene sequences show no considerable compressional tectonic signs in the Hungarian Palaeogene Basin. The southern boundary of the Alcapa Mega-unit is well defined with steep shear zones and bunches of strike-slip structures in the upper crust, along the Mid-Hungarian Shear Zone (CSONTOS, NAGYMAROSY 1998). These strike-slip faults truncated the sedimentary sequences in the Palaeogene sub-basins. Palaeogene volcanism occurred along the Periadriatic Lineament, which may directly linked to the shear zone. These can be followed to Slovenia and the Southern Alps, and can be observed in the Hungarian Palaeogene Basin as well.

Cretaceous–Palaeogene sedimentary units of the Szolnok–Máramaros flysch belt were deposited in the Magura Ocean, while the oceanic crust progressively subducted between the continuously north-eastward moving Alcapa Mega-unit, the Tisza Mega-unit and the stable European Platform. This flysch belt is the pinched, sheared remnant of the oceanic crust between the Alcapa and Tisza Mega-units (SCHMID et al. 2004).

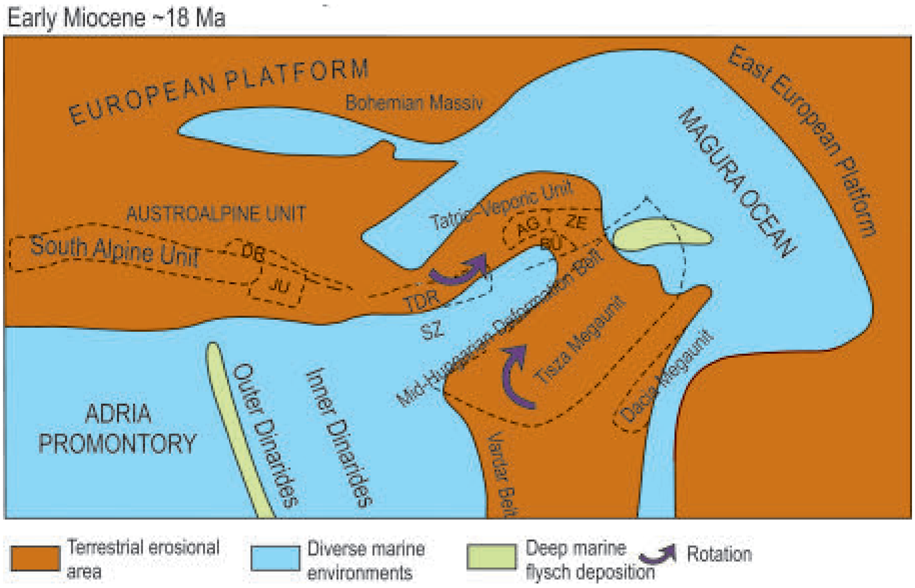


Figure 2.5. Position of the mega-units and units of the Pannonian Basin approx. 18 Ma. (Modified after HAAS [ed.] et al. (2002)

The formation and the main deformation phase of the Mid-Hungarian Zone occurred also in the Palaeogene. During this process the Alcapa Mega-unit moved east–northeastward along this zone and rotated clockwise (MÁRTON 2001). The Alcapa Mega-unit rotated the Tisza Mega-unit into the Magura Ocean, while deforming between them the pinched, sheared blocks of South Alpine relation and sediments of the flysch ocean. (BALLA 1984, 1986; CSONTOS et al. 1992; FODOR et al. 1998) (Figure 2.5).

By the Middle Miocene, the Alcapa and Tisza mega-units had settled into their current position, together with the sheared, consolidated sediments with Southern Alps relationship, altogether with the remnants of the flysch ocean. Between the two mega-units the Mid-Hungarian Shear Zone can be interpreted as the suture of a former ocean (SCHMID et al. 2008). Contemporaneously, basin evolution processes started in the Early Miocene, which led to the formation of the Pannonian Basin.

Pannonian basin evolution

The history of the Pannonian Basin began in a basin system which had been separated from the Alpine Tethys and was named Paratethys. This sea was separated progressively from the ocean in the Palaeogene, and later on its water became fresh when it was transformed into an endemic lake during the Late Miocene. This was completely filled up with sediments by the Pliocene.

The shortening, caused by convergence related to the back-arc basin formation of the Pannonian Basin, can be overspeed the subduction (DEWEY 1980). The basin formation in the territory of the Pannonian Basin was essentially ruled by the dilatational forces generated by the roll-back movements of the subducting slabs. In other parts of the orogenic system, as in the foredeep basins of the Carpathian arc, contemporaneous thrust faults were active and the regime was ruled by compressional tectonics. Main structural phases of the basin evolution can be explained by a thermo-mechanical (MCKENZIE 1978) and isostatic compensational model.

Generally, extension activated the fault planes of nappe systems, with emerging previously buried basement core complexes. These went along with formation of listric faults of low dip angle and transform faults, which altogether create a very characteristic halfgraben structure (HORVÁTH et al. 2006). Exposition of basement core complexes took place mostly along the rims of the basin, while inner basinal parts were dominated by curved listric normal faults. The highly complex structure of the basement, its original complexity and the rotation linked to extensional tectonics originated a very complex trench system. Characteristics of the grabens are linked partly to strike-slip shearing, and partly to extensional normal fault tectonics.

In grabens and basins there are direct quantitative connections between sediment sequences, rotation and the tectonic event history (BALÁZS et al. 2016).

Extension was induced by the extensional stress created by the roll-back of the subducted oceanic slabs beneath the Carpathian arc, and by the potential energy of collapsing nappe structures. The amplitude of extension was several hundreds of kilometres, with a rate of approximately 1.4–1.6% for the whole territory and lithosphere (LENKEY 1999). This rate may

vary from 1.1% to 1.4% (BERECZKI et al 2017) in the individual sub-basins and for the rigid lithosphere, depending on the extensional fault pattern. Lithospheric extension rate of the mantle lithosphere may have been significantly higher than this.

The extensional tectonic regime was complicated by the rotation of mega-units and the extensional force of roll-back subduction beneath the Dinarides. This can be recognised in the southern part of the basin (MATENCO, RADIVOJEVIĆ 2012). According to this process, the vector of the main extensional force was probably rotated counterclockwise (MATENCO, RADIVOJEVIĆ 2012).

The so called Synrift phase, which can be characterised by maximum extension, lasted from Eggenburgian to middle Badenian. Coevally the Alcapa and Tisza mega-units were rotated oppositely in several phases: 80° CCW and 100° CW respectively (MÁRTON, FODOR 2003, MÁRTON et al. 2007, FODOR 2010). During this synrift phase, siliciclastic sequences were deposited in the inner basin in considerable thickness, while only in limited extension at the shorelines.

The extension was brought about by a roll-back mechanism which was accompanied by attenuation of the crust, which resulted in an asthenosphere upwelling (ROYDEN, HORVÁTH 1988). This was strengthened by the asthenosphere flows created by the roll-back process (KOVÁCS I. et al. 2012). In practical terms, the subsidence was due to the isostatic movement of the attenuated and low density crust (i.e. ROYDEN, KEEN 1980). In summary, the thermal flux of the crust increased. After reaching isostatic balance, the start of a thermal balance may also have been achieve, which resulted in a cooling of the crust, which led to a thermal induced subsidence in the Late Miocene.

This period is defined as a postrift phase in the geologic literature (HORVÁTH 2007). The beginning of this postrift phase is not contemporaneous in the Pannonian Basin, but generally started from the end of Sarmatian. To add more complexity, the docking and collision of main units which had by then occurred in the Eastern Carpathian area then resulted in the fall of extensional forces and a quick basin inversion (HORVÁTH 1995). This post-Sarmatian inversion resulted in the folding of synrift deposits and erosion at certain part of the basin, in contrast to the very thick sediment accumulation in other parts of the basin (Figure 2.6). In summary, approximately 5000–7000 metres thick sedimentary sequences were deposited during the postrift phase, which completely filled the basin of Lake Pannon, which became totally isolated due to the contemporaneous emergence of the Carpathians. At this stage the deformation regime was characterised by low amplitude strike-slip and normal faults, and with atectonic compaction.

At the beginning of the Pliocene, subduction was practically terminated due to the gradual rise of the subduction dip angle, a northern compression of the Adria microplate that rotated counterclockwise, and started to dominate the stress field of the realm (BADA et al 2007a, b). Meanwhile, the two main parts of the basement, namely the Alcapa and Tisza Mega-units, were continuously moving NE at different speeds. Relative to all these processes, a compressional stress field came about within the Carpathian Basin. This resulted in the Late Miocene thermic subsidence, which had been changed to inversion in the mountainous area, while subsidence of deep sub-basins still continued (HORVÁTH, CLOETING 1996). This stress field is still active, an assertion supported by in situ stress measurements (GERNER et al. 1999), space geodesy methods (GRENERCZY et al. 2005) and model calculations (BADA et al. 2007a, b).

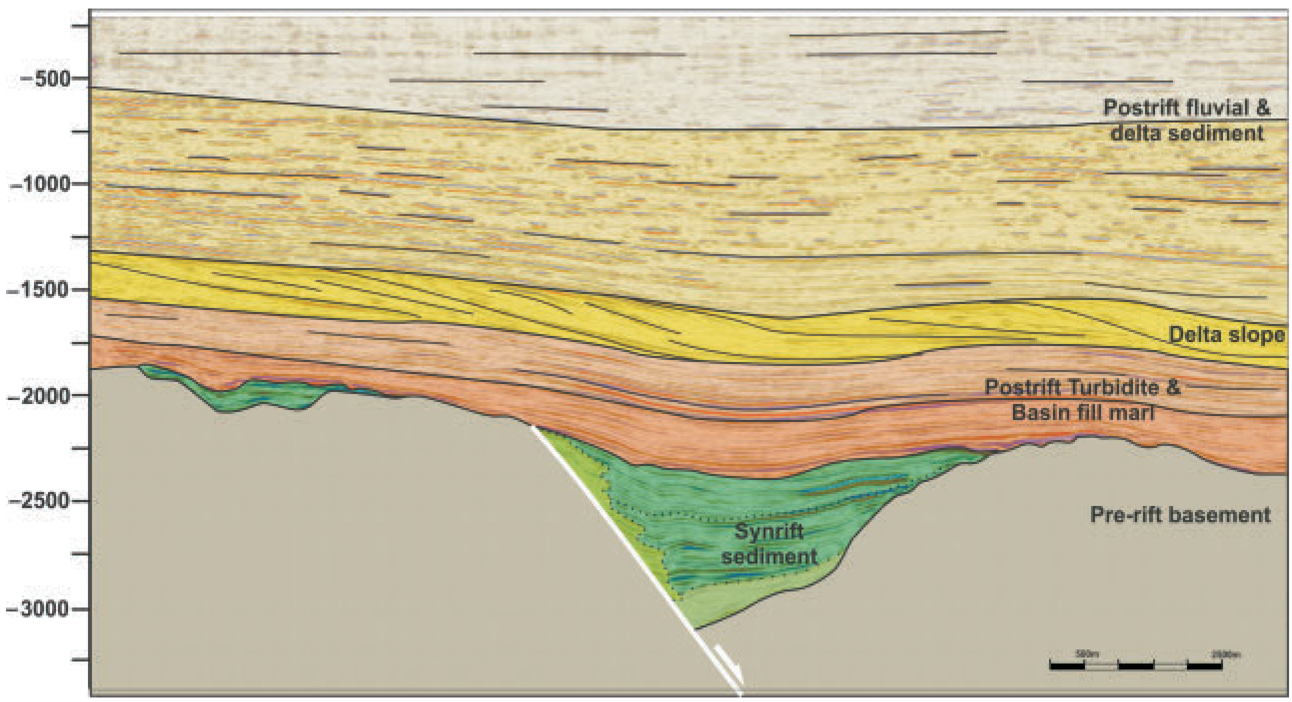


Figure 2.6. Typical synrift halfgraben structure with its postrift cover (interpreted seismic profile)

Depth morphology of the Pannonian Basin

Palaeo-Mesozoic basement depth morphology is shown in Figure 2.7, where pre-Pannonian Miocene deep basins and elevations of the basement can be observed. Three deep areas can be detected in the Danube Basin and its surroundings: the Győr, Nagycenk and Csapod Troughs. Their strike is NNE–SSW, their depth is approximately 4,000–5,000 metres, but the Győr Trough can reach as deep as 8,000 metres. Going further south, to the Zala and Dráva basins, extension of the trenches are E–W, but changes to WSW–ENE as we go farther south from the Dráva Basin. According to seismic data, these trough depths can reach a maximum of 6,000 metres. In southern Transdanubia troughs are about 2,000m deep, but can sometimes reach 3,500 metres (in Tolna county).

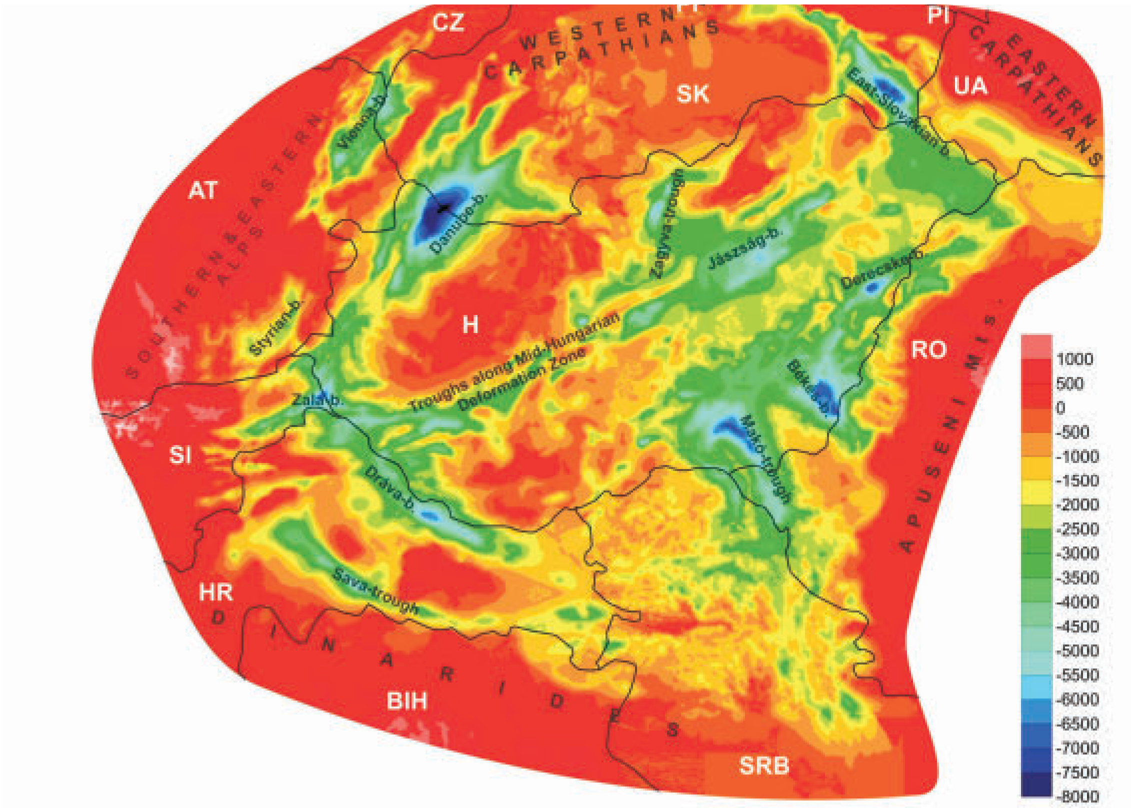


Figure 2.7. Depths of the Pannonian Basin, showing the most significant troughs

Troughs situated in Transdanubia are filled up mostly with pre-Pannonian Miocene deposits, with about 1/3 of them Pannonian.

Along the northern margins of the Great Plain area there are several troughs more than 2,000 metres deep, with complicated basement structure. Their strike is NE–SW, but in the Mátra foreland and right beneath the mountain, some parts of the troughs have a perpendicular strike.

In the Alföld area, a strike of NE–SW direction is also dominant, with the deepest point at Tiszántúl 4,000–6,000 metres. The deepest areas of the Alföld are the Békés and Hódmezővásárhely–Makó troughs, situated in the south-west with a NW–SE strike and a depth of 6,500–7,000 metres.

The basement of troughs infilled with Pannonian sediments is continuously lower from the margins of the Transdanubian Range towards the south-east. This subsidence may reach a depth of 4,000 metres the SE part of the basin. This general picture becomes more detailed with the presence of NW–SE striking structures formed during the Miocene, and emerging ridges in between them.

South-east from the central part of the Transdanubian Range, subsidence of the Pannonian basement continues down to the Tamási trough, and south of this the Mecsek Mountains stop this tendency. West of this area, towards the Dráva Basin, the Pannonian basement again strongly subsides to the depth of 2,500–3,000 metres, but is divided by the Igal, Mezőcsokonya, and Inke–Vése structures.

Another huge part of the Pannonian Basin basement is the deep Danube Basin (Figure 2.7). The Pannonian basement continuously deepens from the SE, practically from the Transdanubian Range, NW toward the Mihályi-high. It reaches a depth more than 6,500 metres. The basement also subsides from the SE of the Sopron–Kőszeg Mountain area, and also reaches a 2,000–2,500 metres depth in the Mihályi-high.

Hydrocarbon geological introduction to the description of Hungarian sub-basins

3

ZSOLT KOVÁCS

Hydrocarbons, crude oil, natural gas

Natural hydrocarbons are multicompound systems, their phase status is determined by their composition, pressure and temperature. Their constituents on normal atmospheric pressure and on 20 °C are divided into crude oil, natural gas and solid phase hydrocarbons. These last ones — in contrast to liquid or gaseous states — are not capable to migrate in the rocks, so they named by their reservoir rock as oil shale, tar sand etc. (SOMFAI et al. 1992). Specific technologies needs for their production so they called as non-conventional or unconventional hydrocarbon occurrences.

Crude oil is a brownish, greenish black fluid, with a density of 650–1,000 kg/m^3 (900 in average) and of high viscosity. More than half of theirs quantity are saturated hydrocarbons, less than 1/3 amount are different types of aromatic hydrocarbons often with sulphur-, nitrogen- and oxygen atoms, the rest is made of high molecular weighted polycyclic hydrocarbons with N-, S- and O compounds. In almost every case, crude oil always contains dissolved gas as methane, ethane, propane, butane, some types may contain hydrogen sulphide (H_2S) as well. From greater depths, sometimes liquid hydrocarbons of clear or light brown colour, with low density (739–779 kg/m^3) and low viscosity, with less than 7–9 carbon atoms can be extracted, which are in gaseous state under the high pressure and thermal conditions of the underground reservoir rocks. This type of a mixture is called condensate or light oil.

Natural gas directly derived from the earth crust is an uncoloured, transparent, odorless gas in its original clear form, a flammable mixture of HC based gases (mainly methane). We can classify combustible and inert or non-combustible (CO_2 or N) gases. Combustible types of natural gases are the first four members of the paraffin-chain as methane, ethane, propane, butane and the hydrogen itself (SOMFAI et al. 1992).

Crude oil and natural gas is made of organic compounds of sedimentary rocks (mostly shales, fine-grained sands, lime mud etc.) deposited in both marine and lacustrine environments. According to their chemical composition, these organic compounds are animal- or vegetable-fats, oils and waxes, which were used to live in place in the basin, or their residues could be transported from greater distance to the former sedimentary basin as pollens, or phyto- and zoo-plankton. Due to the gradual accumulation of the sediments, all strata were compacted, buried deeper and deeper, a process accompanied by a rise of temperature. The thermal minimum of crude oil formation is approximately between 70–150 °C, but may vary widely according to local settings, oil source sediments generally need to be buried at least with a 1,000 metres thick overburden rocks. Formation of natural gas needs even greater burial depth. During the continuous high thermal conditions, the organic matter which is still very similar in its composition to the compounds of living organisms, goes through complex biochemical processes and being transformed into hydrocarbon compounds of natural gas and crude oil. Due to the high underground pressure, compounds of hydrocarbons are starting to migrate from the high pressure places to lower ones, which practically means a flow from their source rock to the surrounding more porous or fractured rock bodies via pores infilled with water. From these porous rocks hydrocarbons migrate as a continuous phase (which means a dark liquid in case of the crude oil) along structural fractures or pores mostly infilled with water. This process is called migration (Figure 3.1).

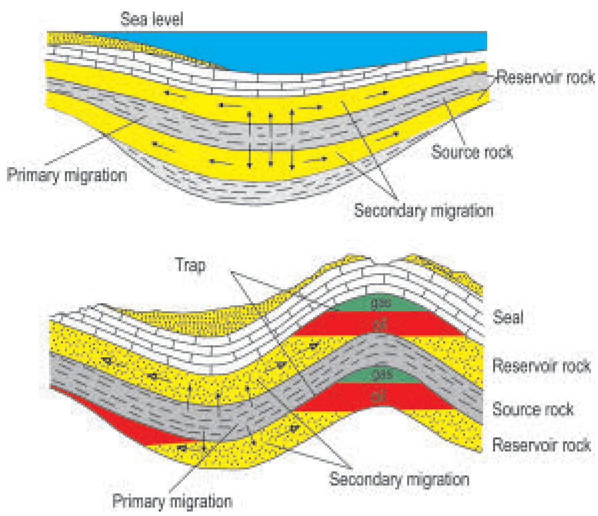


Figure 3.1. Accumulation and migration of hydrocarbons (after TISSOT, WELTE 1984)

Crude oil and natural gas accumulations can be trapped beneath geological structures, where the upward migrating hydrocarbons meet a ductile, non-fractured, impermeable strata which precludes upward migration. These impermeable beds are called cap rock or seal. If this stratum is closed from the edges as well, hydrocarbons accumulate in traps of a reservoir rock beneath the seal. In a trap, different fractures of fluids are layered

along by their weight: natural gas is on the top, below it crude oil, and water is in the lowermost position. This type of accumulation is called oil reservoir with gas cap or gas cap drive reservoir. Sometimes the accumulation does not have a gas cap, but crude oil generally also contains some gas in dissolved form. Gas cap and dissolved gas may in some cases be non-combustible carbon dioxide (CO_2) gas. Very often the whole accumulation is composed of natural gas only (free gas reservoir), mostly of methane, ethane, propane and butane is in smaller amount, as well as varying amount of carbon dioxide gas and nitrogen gas. Rarely CO_2 dominates the gas mixture, if its quantity is over 90%, we call it carbon dioxide gas reservoir.

Conventional reservoirs of oil, natural gas and condensate are trapped in discrete, localised geologic structures and stratigraphic traps, with normal porosity and permeability conditions. These are well-limited structures and hydrocarbons were migrated on a shorter or longer pathway to this accumulation place. Typically the accumulation bounded by a down-dip contact with an aquifer and affected by hydrodynamic influences, such as the buoyancy. Their production is taking place by wells, where oil and gas is can be exploited by the natural pressure of the reservoir or by pumping operations. Sometimes special, higher efficiency methods as water or inert gas injections need to help increase the production. These types of conventionally produced hydrocarbons can be sold after a minimal extraction process.

Non-conventional or *unconventional* reservoirs as e.g. occurences of tight gases in sands with low permeability, shale gas in shales or in marls, coal-bed methane, oil shales with unmatured organic material, shale oils in their source rocks, tar sands, extra heavy crude oils are different from conventional in two point: on the basis of their accumulation type and their technical needs for production. There is no strict boundary between conventional and unconventional accumulations. Related to their source, unconventional hydrocarbons are mostly deposited in their source rock or its very surrounding, and its production needs special, mostly expensive technologies as hydraulic fracturing to exploit hydrocarbons out from the reservoir.

The process of oil and gas exploration

Hydrocarbon exploration, i. e. exploration of oil and gas in its reservoir rock is a process can be divided into staggered stages, which procced from a geological investigation of a certain area of great extension to the identification of the hydrocarbon-bearing structure of a reservoir rock. Its phases can be outlined as follows:

Basin analysis

Origin of oil and gas is basically related to sedimentary basins, so their investigation includes the delineation of the stratigraphic sequence and structural style of the basin filling rocks. In this case basin means a subsided deepening infilled with sediments and surrounded by the older crystalline or igneous rocks of the basin basement.

Basin analysis use different methods to outline the formation of sedimentary space and its infilling with sediments. It determines the time and the structural framework of the basin formation, identifies, localises and put the rocks of the infilling sediments in a detailed, precise time scale and structure. Basin analysis is about to determine the exact age of depositional sequences, physical and chemical parameters of the rocks, outlines them and visualise their extension both horizontally and vertically on maps. In this period of hydrocarbon exploration, geologists and geophysicists are involved to find and outline the extension of potential reservoirs which may store hydrocarbons, the source rocks which may have a matured organic matter content to produce hydrocarbons, and seal rocks which may cover a hydrocarbon trap. They need to investigate physical and chemical parameters of the source, reservoir and seal rocks, identify tectonic movements that affected the basin area. Due to their different physical and chemical parameters, mobilisation and migration of hydrocarbons may vary in different rock types, so the next step is the investigation of the hydrocarbon system.

Recognition of the hydrocarbon system

Studying hydrocarbon systems of a basin means to describe genetic relationships between source rock/rocks and the generated crude oil and natural gas in the accumulations. The aim of these studies is to find any amount of gas or oil in the investigated sedimentary basin, even in small amounts as oil and shows, seeps. The detailed investigation of the hydrocarbon system needs a proper geochemical laboratory analysis of oil- or gas samples.

Hydrocarbon system is a complex natural system that includes all the geologic essential elements and processes needed for oil and gas accumulations to exist (MAGOON, DOW 1994). Hydrocarbons can be of natural gas of thermal or biogenic origin in conventional and unconventional fields, gas condensate, crude oil, natural asphalt or bitumen. The phrase "system" refers to all elements and processes connected together, which were affected the origin or accumulation of hydrocarbons. These essential elements are the following:

— a source rock, which is a sedimentary rock with thermally matured high organic matter content, which hydrocarbons are originated from;

— reservoir rocks are mostly siliciclastic or carbonate rock formations which may contain natural accumulations of moveable hydrocarbons;

— cap rocks or seals, which ensure the trapping with the overburden rocks or covers which determinate the thermal-, pressure- and compaction ratios of the rocks below.

The processed involved:

— formation of the trap system in time and space;

— generation, migration and accumulation of hydrocarbons.

Maturity of hydrocarbons and their release from their source rocks needs enough time and temperature in geological sense, which are provided by the sediments continuously deposited on the top of the source rock. On the base of the knowledge of a hydrocarbon system allows us to outline its geographic and geological extension, which means the distance from the middle of the onetime or still active matured source rock to the furthermost known existing accumulations.

Hydrocarbon systems may be investigated and researched in many ways, but there are three main types on the basis of exploration status. The system is well known if there are proved geochemical correlations exist between the source rock and its hydrocarbon occurrences. We use term "hypothetic hydrocarbon system" if the source rock can be outlined and identified due to geochemical investigations, but there is no direct, or well-defined correlation between the source rock and datasets of the hydrocarbon accumulations. A system is speculative, if the source rock, as well as the hydrocarbon occurrences are just assumed due to geophysical or geological exploration data but not proved yet.

Determination of a hydrocarbon play

Based on knowledge of a hydrocarbon system in the studied sedimentary basin, groups of structures or formations separable which are similar to each other from geological-sedimentological point of view and which are assumed to be a group of reservoirs. In this period of the investigation, possible hydrocarbon bearing reservoir structures or traps are analysed by their geologic features, with involving geochemical and geophysical methods and data. Investigation includes a research on source, reservoir and seal rocks, migration routes, a trap system infilling with hydrocarbons, the saturation of hydrocarbons and estimation of the total volume of recoverable hydrocarbons that are originated from a single part of matured source rock.

Designation of a prospect as a drilling target

Prospects are individual present-day traps that are sufficiently well defined geophysically and geologically and are to represent viable drilling target of undiscovered commercial oil/gas accumulations. In this phase, exploration experts are searching for such a kind of determinable structures with possible oil and gas reservoirs that are ready to visualise on detailed geological contour maps and their knowledge is as well documented to be eligible for exploration drilling. Geologists have to identify the undiscovered estimated recoverable resources, while economists can do probabilistic production estimates, and cost recovery on the basis of provided facilities, technology and all technical and economic possibilities. Successful handling of a research prospect needs a risk and reward evaluation, due to the highly risky nature of hydrocarbon exploration.

If the petroleum exploration is proven to be successful with an exploratory drilling, the prospect is ready to be converted into a commercial field project. Oil/gas field is a mining term related to producing of discovered hydrocarbons, a certain area of sub-areas connected to each other on the basis of geologic or production point of view, usually with several dozens of producing wells. A reservoir is a part of an oil field which can be separated from its non-hydrocarbon bearing surroundings by its unique hydrocarbon content. Evaluation of oil fields although are along with huge effort of exploration and evaluation of reservoir parameters, but are classified into the production phase of exploration process.

Completion describes the process of bringing a well into production after the well has been drilled to the depth where oil or gas is expected to be found. Completion sub-processes are field limiting, locating development, injection and service wells, and during the workover repetition of 3D seismic surveys are for monitoring the supplies. Of course, these information may widen our geological and geophysical knowledge of certain sedimentation and exploration areas, for instance it is possible to refine the sequences of a sedimentary basin on the basis of wellsite geological and geophysical data and by laboratory measurements on core, cutting and fluid samples data. Studying of numbers, situation, and resource quality and quantity data of discovered fields are also support localising other hydrocarbon resources in a different part of the same sedimentary basin.

Sub-basins and hydrocarbon systems in the Hungarian part of the Pannonian Basin

Hungarian oil and gas exploration is restricted geographically to the area of the Carpathian Basin surrounded by the chains of the Alps, Carpathians and Dinarides. This is the so-called Pannonian Basin, which is, from geological point of view, a sedimentary basin which extends over the national borders of our time.

The so-called Total Petroleum Systems (TPS) of the inner Carpathian area are visualised on Figure 3.2 after Dolton (2006). Scope of matured source rocks are coloured green for the Neogene–Neogene/Mesozoic sediments, and red for the Palaeogene's. Dolton separates six TPS, from which four are situated partly in the present area of Hungary. These are the

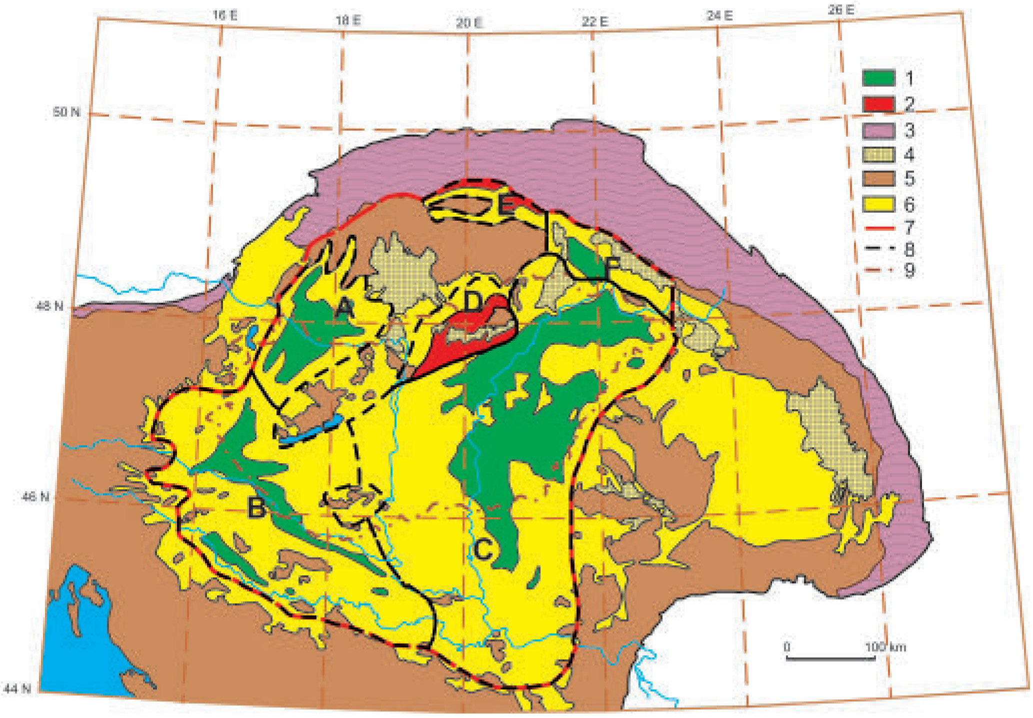


Figure 3.2. Extension of the Pannonian Basin, and its main total hydrocarbon (petroleum) systems after the map of DALTON (2006) completed for the USGS

Captions: A = Danube Neogene, B = Zala–Dráva–Sava Mesozoic, C = Great Hungarian Plain Neogene, D = Hungarian Palaeogene, E = Central Carpathian Palaeogene, F = Transcarpathian Neogene Basin

1. Area of matured source rocks for Neogene and mixed Mesozoic/Neogene total hydrocarbon systems, 2. Area of mature source rocks for Palaeogene total hydrocarbon systems, 3. Outer Alpine–Carpathian flysch belt, 4. Outcrop of Neogene calc-alkaline volcanic rocks, 5. Inner Alpine – Carpathian foldbelt and Dinarides, 6. "Tertiary" Pannonian Basin boundary, 7. Extension of total hydrocarbon systems situated in the Pannonian Basin (excluding Vienna and Transsylvanian Basins reserves), 8. Total hydrocarbon system boundary, 9. Boundary of Hungary

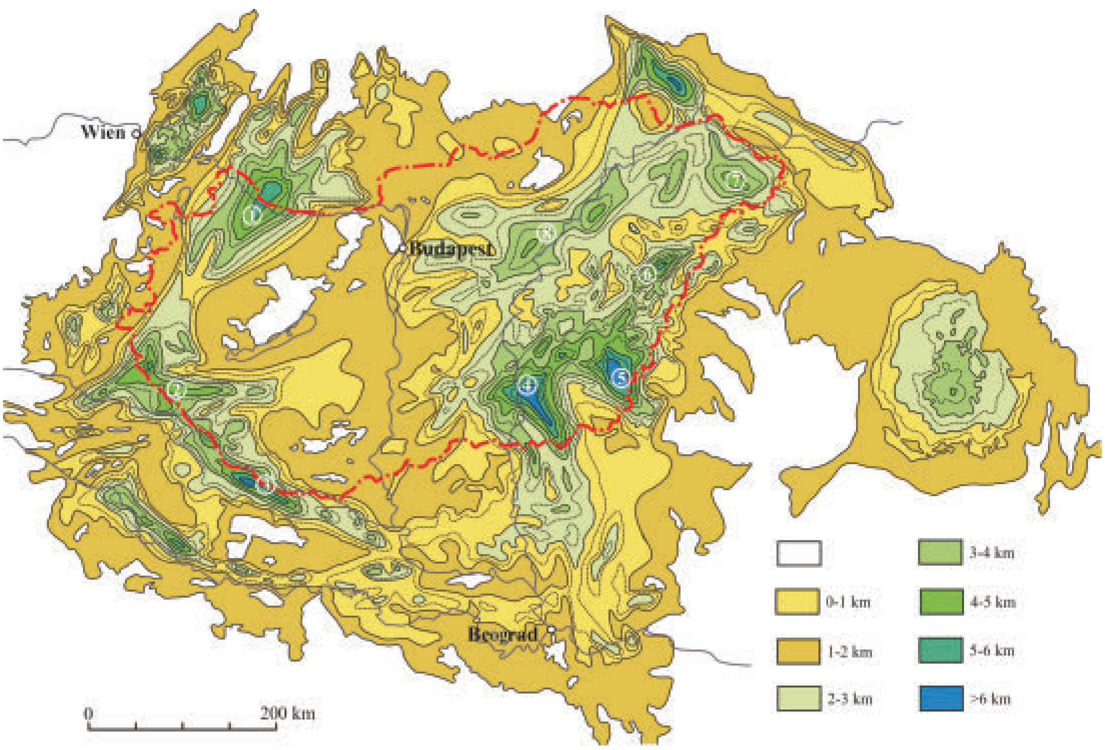


Figure 3.3. Thickness ratios of Neogene deposits, after HORVÁTH, ROYDEN (1981), with outlining the most important present-day depressions. White areas are surface outcrops of pre-Neogene basement

1. Danube Basin, 2. Zala sub-basin, 3. Dráva sub-basin, 4. Makó Trough, 5. Békés Basin, 6. Derecske Trough, 7. Nyírség sub-basin, 8.Jászság sub-basin

Danube Basin at the Kisalföld (Little Hungarian Plain) region, the Zala–Dráva Basin at the southern part of Transdanubian Hungary, the basin of the Great Hungarian Plain at the south-eastern part of country and the Hungarian Palaeogene Basin in north-east. Thickness ratios of Neogene sedimentary sequences of the Pannonian Basin are shown on Figure 3.3, after Horváth (1985).

In the Chapter 4, the work of Dolton (2006) is followed for division of sub-basins. Concerning the Great Hungarian Plain region, the Kiskunság, the Szeged Basin, the Battonya–Pusztaföldvár High, the northern part of Nagykunság with flysch basin basement, the southern part of Nagykunság, the Bihar and the Nyírség areas are separated (Figure 3.4, Table 3.1).

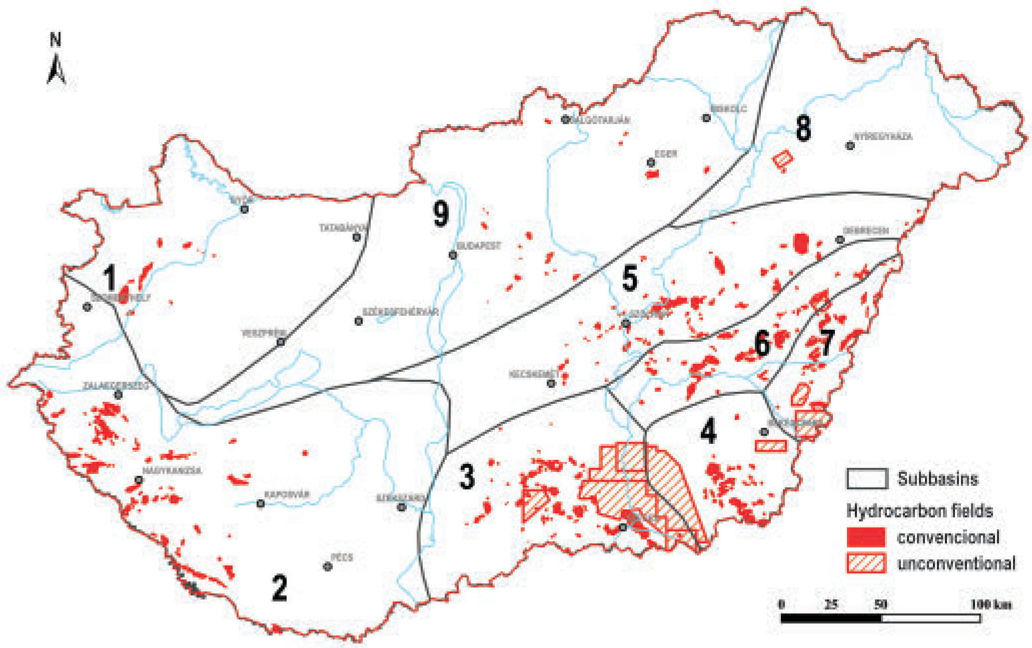


Figure 3.4. Separated areas mentioned in this book

From the 1950's onwards, experts of the Hungarian Oil and Gas Trust (OKGT) prepared the evaluation of the domestic oil- and gas exploration, with estimating the undiscovered resources in a detailed hydrocarbon prognoses for five years ahead. In 1997, following the traditions of earlier estimate reports, the Hungarian State Geological Institute, together with the Loránd Eötvös Geophysical Institute and the Hungarian Geological Survey constituted a joint project on the "Hydrocarbon-potential of Hungary on 31st December, 1995", which covers the evaluation of the discovered and undiscovered conventional resources (Juhász, Kummer szerk. 1997). According to this report, there is a direct link between the Hungarian oil- and gas occurrences and the stratigraphic and structural features of the Pannonian Basin. Considering this point, there are several regional areas of hydrocarbon accumulations, which are descripted in the sub-basin chapter (Chapter 4) in details, and which can be characterised by the followings:

Table 3.1. Numbering and denominations of certain areas

No	Region
1	Little Hungarian Plain
2	Zala and Dráva Basin
3	Kiskunság and Szeged Basin
4	Battonya-Pusztaföldvár High
5	Nagykunság northern part with „flysch" basement
6	Nagykunság southern part
7	Bihar
8	Nyírség
9	Hungarian Palaeogene Basin

— hydrocarbon accumulation areas are determined by the main structural movements related to the Austrian orogenic phase modified later by the younger orogenic phases in different ways;

— all known hydrocarbon accumulations are connected with Neogene sedimentary basin areas with huge siliciclastic deposits, mostly located on their marginal areas (Figure 3.5 and Table 3.2);

— main migrational routes of hydrocarbons are along with discordance surface morphology of the pre-Middle Cretaceous basement and determined by its thermal- and pressure ratios, and additionally younger discordances, their surface morphology, and their thermal- and pressure system was also played a role in the evolution of migrational routes;

— hydrocarbon accumulation zones are determined by the Neogene and Palaeogene structures and sequence

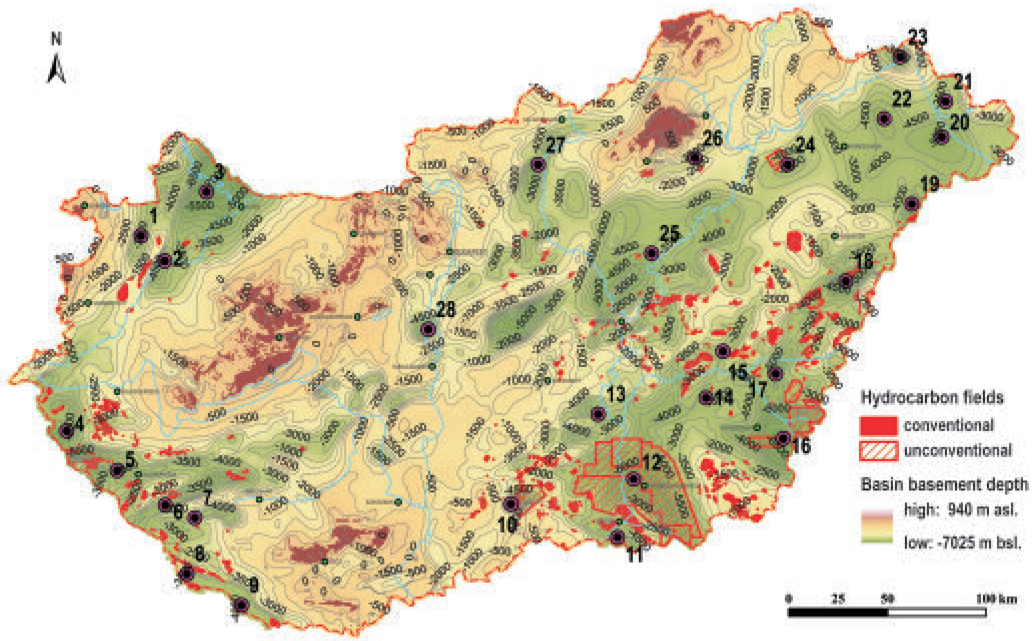


Figure 3.5. Troughs, deep zones and depressions of the pre-Cenozoic basement of the Pannonian Basin

morphology, thrusts and foldings of the basement, and the thermal- and pressure ratios of the Palaeogene and Neogene sequences

— processes of migration and trapping of hydrocarbons are also affected by vertical fault systems, so in several cases the NW–SE striked fault zones, which are perpendicular to the WSW–ENE striked main fault zones, were the most important factors in migration and trapping.

All these conclusions are accepted as valid nowadays as well. Changes were made in the point of view of the exploration

Table 3.2. Troughs, deep zones and depressions of the basement of the Pannonian Basin

No	Troughs/depressions	Regions/Sub-basins	Depth (m)
1	Csapod trough	Danube Basin (Little Hungarian Plain)	3000–4000
2	Kenyeri deep	Danube Basin (Little Hungarian Plain)	3000–5000
3	Győr deep	Danube Basin (Little Hungarian Plain), Kunsziget-Lébény-Kóny	6000–7000
4	Őrség deep	Zalai-medence, Csesznek-Resznek-Lenti-Lovászi	4000–6000
5	Nagykanizsa deep	Zala Basin, Budafa-Letenye-Nagykanizsa-Nagyszakácsi-Mezőcsokonya	4000–5000
6	Gyékényes-Inke depression	Somogy-Dráva Basin	3000–5000
7	Somogyudvarhely-Kadarkút deep	Somogy	3000–4000
8	Drávavölgy depression	Pitomaca-Barcs-Nyugat	6000–7000
9	Drávavölgy depression	Felsőszentmárton-Zaláta	3500–4500
10	Kiskunhalas deep	Kiskunság	4000–5000
11	Kömpöc-Mindszent depression	Szeged Basin	4000–5000
12	Makó-Hódmezővásárhely Trough	southern part of Great Hungarian Plain	3500–7000
13	Alpár-Csongrád depression	southern part of Great Hungarian Plain	4000–4500
14	Fábiánsebestyén-Hunya-Mezőberény trough	southern part of Great Hungarian Plain	4000–5000
15	Örménykút-Ecsegfalva trough	southern part of Great Hungarian Plain	3000–3500
16	Békés-Gyula deep	south-eastern part of Great Hungarian Plain, Békés Basin	6500–7000
17	Doboz-Vésztő-Darvas trough	south-eastern part of Great Hungarian Plain	4000–5000
18	Derecske trough	south-eastern part of Great Hungarian Plain	4500–6000
19	Penészlek trough	southern edge of Nyírség	4500–5500
20	Nyírkáta-Nagyecsed-Győrtelek depression	Nyírség	4000–5000
21	Szamosszeg deep zone	Nyírség	3500–4000
22	Nagyhalász-Kállósemjén deep zone	Nyírség	3500–4500
23	Komoró-Nyírlövő depression	Nyírség	2500–4000
24	Tiszavasvári depression	Northern Great Hungarian Plain, Nyírség	3000–4000
25	Jászság Basin	Örkény-Jászkisér-Tiszafüred deep sub-basins	3500–5000
26	Vatta-Maklár Trough	Northern Hungary, Hungarian Palaeogene Basin	2000–3000
27	Zagyva Trough - Etes Trough - Ózd-Basin	Northern Hungary, Hungarian Palaeogene Basin	4000–5000
28	Adony depression	Northern Hungary, Hungarian Palaeogene Basin	3000–5500

process, and the conscious application of hydrocarbon system logic. With the development of exploration methods, the amount, accuracy and resolution of information can be gained about the research areas increased, therefore identification of smaller geological structures and less significant facies changes within one formation, so determination of structures with smaller potential hydrocarbon accumulations became possible.

Litho- and chronostratigraphic nomenclature of the Neogene

Herein, on Table 3.3 and Figure 3.6 we summarised the current status of geological and lithological nomenclature of Hungarian Neogene deposits, as well as their relation to previous studies and its connections to the international charts. Here, due to its widespread usage among professionals, we use Lower Pannonian as a synonym of Peremarton Formation Group, as Upper Pannonian for the Dunántúl Formation Group in lithostratigraphic point of view as well.

Table 3.3. Changes in Neogene chronostratigraphy

Traditional stages/ages (not recommended)				Stages/ages accepted in Hungary (from the 1980s)		Internationally accepted stages/ages		Group
Quaternary	Q			Quaternary				
Pliocene	Pl	upper part of Upper Pliocene (Levantian)	Pl3	Pannonian (s. l.)	Upper Pannonian (Pa2)	Pl	Pliocene	Dunántúl Group
		Upper Pliocene (Upper Pannonian)	Pl2					
		Lower Pliocene (Lower Pannonian)	Pl1		Lower Pannonian (Pa1)	M3	Upper Miocene	Peremarton Group.
Miocene	M	Sarmatian	M3	Middle Miocene	Sarmatian (Ms)	M2	Middle Miocene	
		Tortonian	M2		Badenian (Mb)			
		Helvetian		Lower Miocene	Karpatian(Mk)	M1	Lower Miocene	
					Ottnangian (Mo)			
		Burdigalian	M1		Eggenburgian (Me)			
		Aquitanian			Egerian (Mer)			

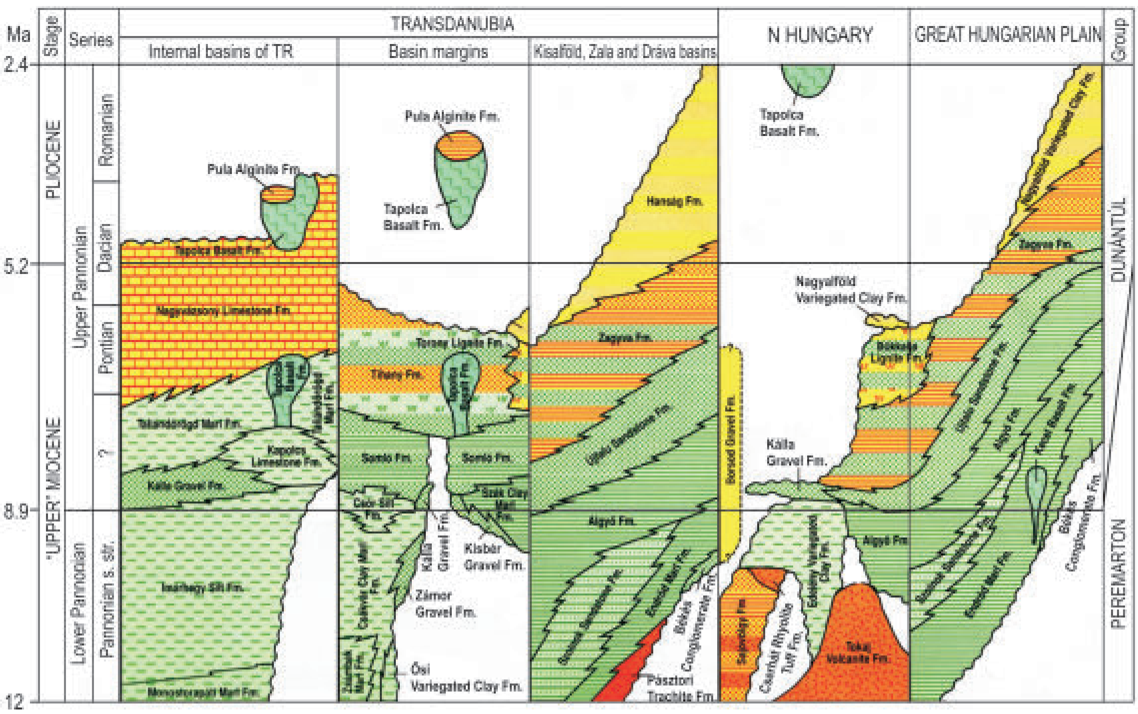
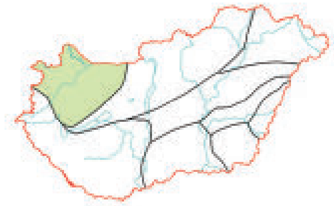


Figure 3.6. Litho- and chronostratigraphic chart of Pannonian formations (after CSÁSZÁR ed. 1997)

Hydrocarbon exploration areas in Hungary — Northern Transdanubia – Little Hungarian Plain (Danube Basin)



4.1

Ildikó Selmeczi

Exploration history

The historical background to the hydrocarbon explorations in the Little Hungarian Plain (Kisalföld in Hungarian) goes back to the second half of the 1910s. Based on his geological investigations, Ferenc Pávai Vajna assumed low-angle folds of E–W direction in the southern part of the area (Körmend, Kőszeg, Szombathely), but they were not confirmed by subsequent explorations. The summary on near-surface formations was provided by Szádeczky-Kardoss (1938).

Hungary contracted Eurogasco (later MAORT) in 1933, under which this company was granted the hydrocarbon explorations and mining explorations rights for Transdanubia as the whole. Modern petroleum explorations in the Little Hungarian Plain started subsequently under the direction of Simon Papp, with Eurogasco. In parallel with the surface geological mapping efforts undertaken by László Strausz and Miklós Kretzoi, geophysical measurements were carried out as well. Measurements using the Eötvös torsion balance (field pendulum) were carried out from 1933 to 1944 by Eurogasco, later MAORT, mostly in Transdanubia and this was carried out by Raul Vajk, Szilárd Oszlaczky, Viktor Scheffer and László Facsinay, among others. As the result of this work, the Mihályi–Répcelak basement high structure has become known in the Little Hungarian Plain. Magnetic anomalies at Szombathely, Szeleste, Pásztori and Dunaremete were detected with the help of geomagnetic measurements led by Viktor Scheffer. The first seismic measurements were completed in the summer of 1935 on the Mihályi structure, where an elevation was shown in line with the gravity anomaly (Vajk 1943, Lányi 1959, Kőrössy 1987).

Following geological investigations and geophysical measurements, the first oil exploration wells were drilled on the Mihályi structure between 1935 and 1946. There, natural gas occurrence with high CO_2 content was discovered in the Little Hungarian Plain (Danube Basin). After a couple of years, intermission exploration works started again in 1953: geophysical measurements were carried out up to the 1960s in extensive areas and a number of exploratory wells were drilled. Regional gravity measurements in the years 1933–1944 suggested that the continuation of the Mihályi structure could also be found around Mosonszentjános (today: Jánossomorja). The well M–4 was drilled in 1944 NNE of Mihályi to explore the northern partial maximum. The well proved to be dry. Later, it became known that this structure was separated from the Mihályi structure by a trough of SW–NE direction. On the top part of the Mosonszentjános structure five less elevations were found. These were explored by wells Mos–1 and Mos–2, and then by the M–4 well in 1971. Exploration was justified by traces of oil encountered in the wells of the neighbouring Austrian village Pátfalu (Podersdorf). Oil and gas shows were observed in well M–4, but these could not be properly investigated after the casing operation. Mos–1 and Mos–2 wells found no significant traces of hydrocarbon, so the exploration was not continued (Kőrössy 1987).

Two key exploration wells were drilled in the 1950s in the Szany and Vát area, respectively, then exploration were conducted in the Pinnye and Bük, as well as in the Nagyigmánd areas. These areas had been better understood in the meantime through geophysical measurements, and finally brought results in terms of hydrocarbon explorations. The Ikervár–1 well also discovered natural gas in 1962. Several wells in the area became productive, which again gave an impetus to exploration drilling in the Little Hungarian Plain area. Due to the lack of new results, however, this kind of activity substantially diminished following 1966 (Kőrössy 1987).

Exploration of greater depths started in 1966 along the Pásztori structure (Pásztori–1 well), followed by the exploration of deeper parts of the basin at Celldömölk in 1967 and 1968 (Dabrony–1 well). Greater depths were to be explored in the western part of the Győr deep basin zone by the Bősárkány Bő–1 well (1969), and in the Csapod Trough by the Csapod–1 well (1970). Both of these were dry (Kőrössy 1987). The 2,400 m-deep Lébény–2 well (1981) was drilled in the deeper part of the deepest area in the Danube Basin, i.e. the Győr depression; it was stopped in the younger Pannonian formations, and provided no useful hydrocarbon information. Exploration of the Mosonszolnok–Rajka area — where 1.5 million tons of hydrocarbon resources were estimated (Tormássy 1980) — started in the 1970s. Natural gas traces were found in Monostortétény (Tadten) and Pomogy (Pamhagen) wells, in Austria, justifying those efforts. This was when the Mosonszolnok Msz–1 (1976), Rajka Raj–1 (1976) and Mosonszolnok Msz–2 (1977) exploration wells were drilled, with the additional aim of penetrating Neogene beds and reaching the basement. Since all three wells were dry, continued drilling exploration was not found to be justified until re-evaluation of the seismic data was completed. Besides the gravity–seismic maximum explored by the Msz–1 well, three additional maximum levels were shown on the seismic depth map of the basement surface in the Mosonszolnok area, reaching depths of –2,350 m, –2,900 m and –3,350 m, respectively. Clarification of this result was listed as a task for the future (Tormássy 1980, Kőrössy 1987).

In 2005 Magyar Horizont Energia Kft (Hungarian Horizon Energy Ltd) obtained the right to hydrocarbon explorations in the Little Hungarian Plain. During this period, the HHE–Csíkvánd–1 well (2009) and HHE–Malomsok–1 well (2012) were drilled to the SW of Tét. Despite some evidence of hydrocarbon presence, both were dry holes.

Mol (Hungarian Oil and Gas Plc) explored the western foreland of the Transdanubian Range around Döbrönte between 1996 and 2004, but no commercially recoverable hydrocarbon resources were found there (TURTEGIN et al. 2004).

Geological overview

The basement of the Little Hungarian Plain (Danube Basin) is of African origin, belonging to the Alcapa Mega-unit of complex structure. It consists of several tectonic units, such as parts of the Penninicum and the Austroalpine nappes reaching into Hungary (Lower and Upper Austroalpine Unit, as well as the Transdanubian Range Unit) (HAAS et al. 2010; Figure 4.1.1).

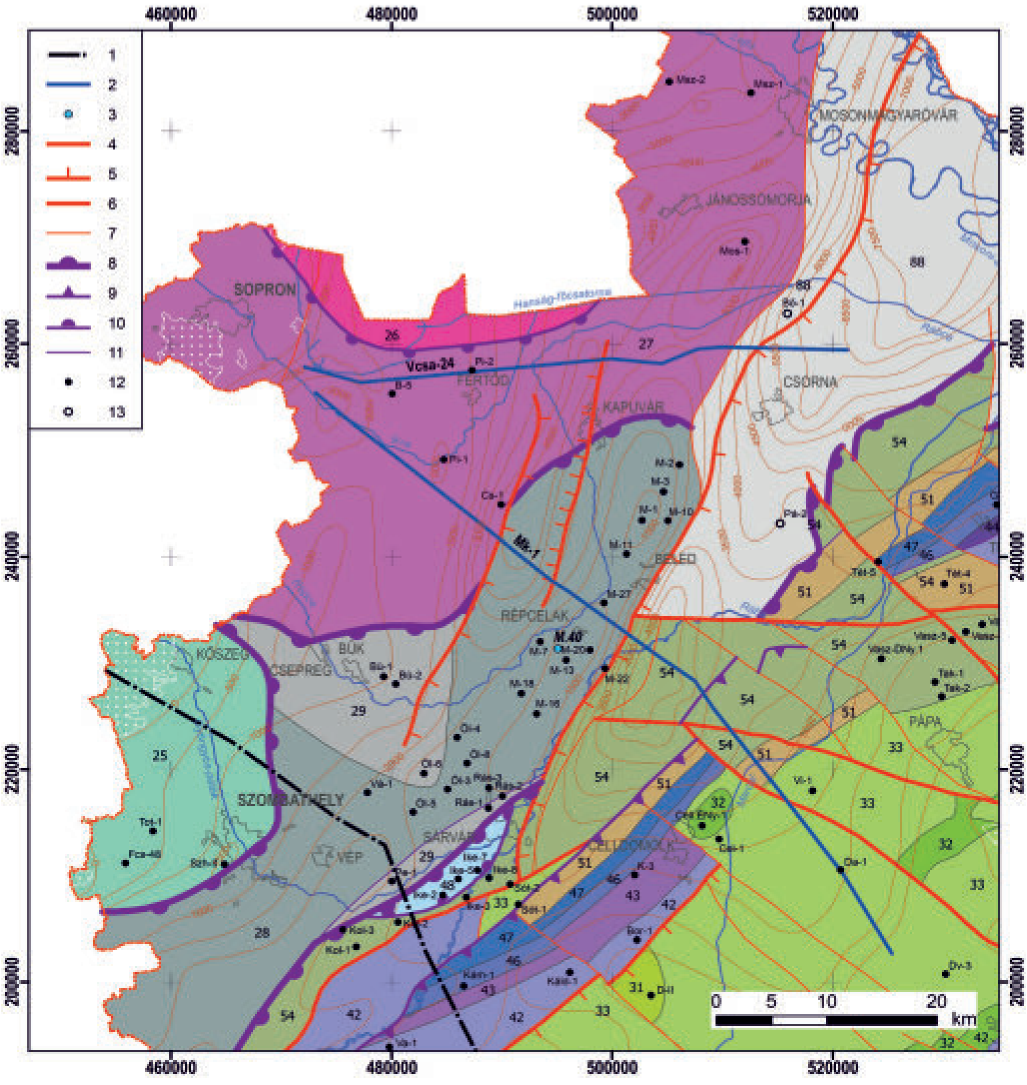


Figure 4.1.1. Pre-Cenozoic geological map of the Northern Transdanubia – Little Hungarian Plain (Danube Basin) region (HAAS et al. 2010)

Elements of legend: 1. boundary of the sub-basin, 2. trace line of the sample 2D seismic profiles in this chapter, 3. location of wells including sample logs in this chapter, 4. second-order Cenozoic tectonic line, 5. second-order Cenozoic normal fault, 6. second-order Cenozoic wrench fault, 7. third-order Cenozoic tectonic line, 8. first-order Mesozoic nappe boundary, 9. second-order Mesozoic overthrust, 10. second-order Mesozoic nappe, 11. third-order Mesozoic tectonic line, 12. wells reaching the pre-Cenozoic basement, 13. wells stopped above the pre-Cenozoic basement.

Legend for geological formations: 25. low-grade metamorphic Jurassic–Lower Cretaceous formations (phyllite, meta-sandstone, greenschist), 26. medium- and high-grade polymetamorphic formations (amphybolite, gneiss, mica), 27. medium grade polymetamorphic formations (gneiss, mica), 28. Variscan low-grade metamorphic Lower Palaeozoic formations (phyllite, meta-sandstone), 29. Devonian marble, calcareous slate, 31. Senonian continental siliciclastic and swamp formations, 32. Senonian platform limestone, 33. Senonian basinal limestones and marls, 42. Carnian–Norian platform dolomites, 43. Carnian basinal marls and limestones, 44. Anisian–Ladinian basinal limestones, cherty limestones with tuffaceous intercalations, 46. Anisian shallow marine limestones and dolomites, 47. Lower Triassic shallow-marine, siliciclastic and carbonate formations, 48. Mesozoic very low-grade metamorphic formations, 51. Middle–Upper Permian continental siliciclastic formation, 54. Variscan low-grade metamorphic, Early Palaeozoic formations (phyllite, limestone, metavolcanics), 88. inadequately evaluable or unknown basement

In the western and north-western part of the Little Hungarian Plain (Danube Basin) the basement is built up of the Palaeozoic metamorphic rocks of the Austroalpine nappes, below which the Penninicum — belonging to the structure of the Western Alps — crops out in the form of a nappe window. Structurally the Transdanubian Range Unit, constituting the basement in the eastern, south-eastern part of the Danube Basin, which is the nappe in the uppermost structural position in the Austroalpine nappe system, is basically free from any metamorphic impact (TARI 1994, FODOR et al. 2003, TARI, HORVÁTH 2010, BUDAI, KONRÁD 2011) (Figure 4.1.2). The boundary between the Transdanubian Range Unit and the Upper Austroalpine Unit coincides with the Miocene strike-slip movement and normal fault-system running along the Rába river and known as the Rába Line. The boundary of the large structural units can also be considered as a Cretaceous nappe boundary (TARI 1994; FODOR, KOROKNAI 2000, FODOR et al. 2003; HAAS et al. 2010, 2014; TARI, HORVÁTH 2010). The Transdanubian Range Unit is separated from the Vepor Unit in the north by the Diósjenő–Ógyalla (Hurbanovo) Line, and borders the Bükk Unit along the Darnó Zone in the north-east. The southern boundary is constituted by the Periadriatic–Balaton Zone (KÁZMÉR, KOVÁCS S. 1985, BALLA 1988, TARI 1994, FODOR et al. 1998).

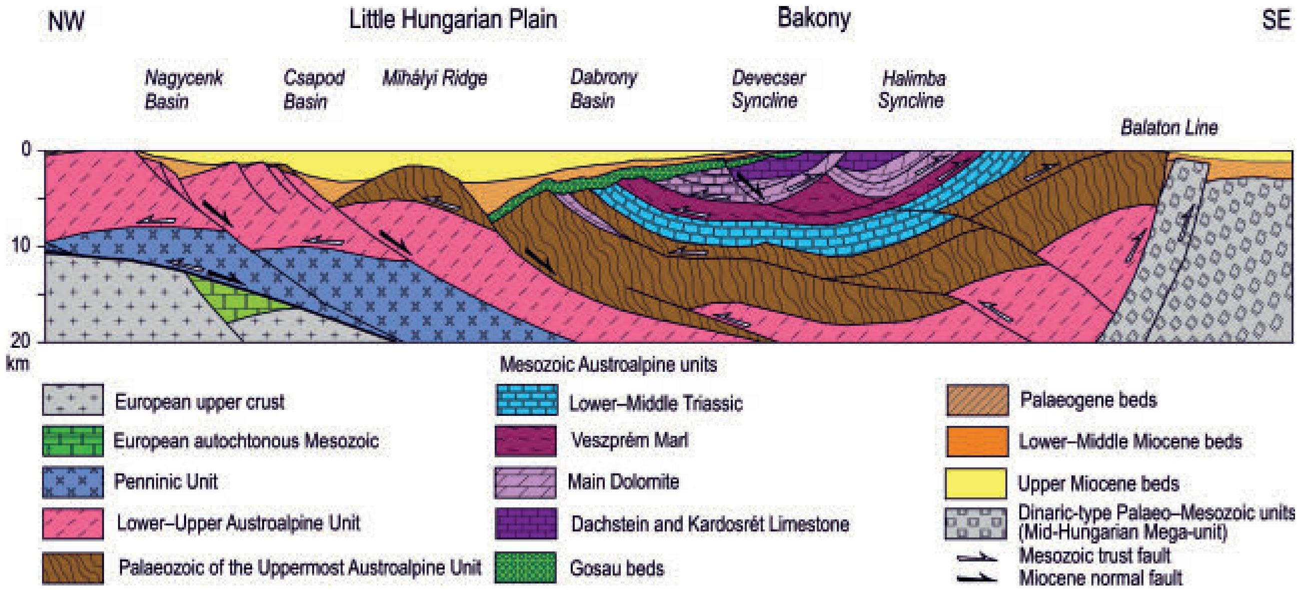


Figure 4.1.2. The structural position and geological build-up of the Austroalpine nappes (BUDAI, KONRÁD 2011 after TARI, HORVÁTH 2010)

Palaeozoic and Mesozoic formations of the Transdanubian Range Unit form a large syncline of SW–NE strike; in the axial zone thereof younger Jurassic–Cretaceous sequences occur, whereas towards the margins increasingly older formations can be found.

The formation of the Danube Basin started in the syn-rift phase of the Pannonian Basin evolution, during the Karpatian–Badenian ages of the Miocene. However, the most intensive period of subsidence here can be dated to the post-rift phase in the late Miocene after the Sarmatian age, thus the thickest basin filling successions belong to the Pannonian (HORVÁTH et al. 2011, KOVÁCS, Zs. ed. 2013).

A significant elevation in the bottom of the Danube Basin is the Mihályi Ridge, stretching in NE–SW direction along the Mihályi–Répcelak–Uraiújfalu line. To the west, parallel to the latter, runs the Csapod Trough, which — according to seismic profiles — is filled with Miocene and younger sediments in a thickness of more than 5,000 metres. The trough runs towards the south into a widening sub-basin with a basement depth of 2,000–3,000 metres; it is connected to the Zala Basin. The Kenyeri Trough, transiting into the Győr zone towards the NE, can be found east of the Mihályi Ridge. Based on the seismic profiles, the thickness of the basin-fill sediments reaches or even exceeds 7,000–8,000 metres to the west of Győr. Towards the south in the Kenyeri Trough area, 4,000–5,000 m thickness values are known. The total thickness of the Neogene and Quaternary sequences in the continuation of the Győr deep zone in Slovakia, i.e., in the Gabčíkovo sub-basin, reaches as far down as 9,500–10,000 m (VASS et al. 1990, KILÉNYI, ŠEFARA (eds) 1989, HRUŠECKÝ et al. 1996).

Basement formations

The basement of the Danube Basin located W and NW of the Rába Line is formed of rocks which have undergone low- and medium-grade metamorphism (Penninicum, Lower and Upper Austroalpine Unit). In the areas to the east and to the south-east of the Rába Line, the basement is composed of Early Palaeozoic, low-grade metamorphic rocks of the

Transdanubian Range Unit and non-metamorphic Late Palaeozoic – Mesozoic (Permian–Cretaceous) sedimentary sequences.

The lowermost tectonic unit of the western Danube Basin is the Penninicum or Penninic Unit, formed of low-grade metamorphic rocks, Jurassic – Early Cretaceous formations (phyllite, meta-sandstone, meta-quartzite, greenschist, serpentine, and talc) (Figure 4.1.1).

In the west and north-west the basement is made up of medium-grade polymetamorphic formations (amphibolite, amphibole- and biotite-schist, mica and gneiss) of the Lower-Austroalpine Unit. Formations of the Upper Austroalpine Unit (phyllite, meta-vulcanite, poorly metamorphic carbonates, etc.) appear east and south-east of the Penninic Unit and the Lower Austroalpine Unit in the basement of the Danube Basin.

The Transdanubian Range Unit is made up of the several hundred-metre thick Early Palaeozoic low-grade metamorphic, non-metamorphic Late Palaeozoic rocks and Mesozoic formations. The Mesozoic sequences overlie the bedrocks. The units of the Lower Triassic formations occurring parallel to the strike of the Transdanubian Range form the basement in the Győr, Győrszemere, Tét, Celldömölk and Kám areas. Based on wells drilled on the south–south-eastern limb of the "Tét anticline", the 250–300 metre-thick siliciclastic and carbonate succession of shallow shelf facies is made up of the Arács Marl, Köveskál Dolomite and Hidegkút Formation, as well as the Csopak Marl. The extension of the Middle Triassic (Anisian) shallow-marine–lagoonal beds (Aszófő Dolomite, Iszkahegy Limestone, Megyehegy Dolomite, Tagyon Limestone), and of the deep-water carbonates (Felsőörs Limestone) — of the basins opened up in the middle of the Anisian due to extensional tectonics — can be traced in the neighbourhood of the Lower Triassic band (HAAS, BUDAI ed. 2014). During the Ladinian, pelagic carbonate sedimentation (Vászoly Formation, Buchenstein Limestone) took place in the basins, accompanied by the formation of volcanic structures. Pelagic carbonate sedimentation in the basins (developed in the Middle Triassic) was replaced by siliciclastic sedimentation in the beginning of the Late Triassic (Veszprém Marl Formation). After deposition of the several hundred metre-thick marl succession, the basins filled up and a large carbonate platform formed (Main Dolomite and Dachstein Limestone).

Jurassic – Lower Cretaceous basement formations with different facies (i.e. the Kardosrét Limestone, Pisznice Limestone, the Pálihálás Limestone of "ammonitico rosso" facies, the Szentivánhegy Limestone with brachiopods and belemnites) are known only sparsely in the Northern Transdanubia – Little Hungarian Plain region. The crinoideal limestone of pelagic basin facies (Tata Limestone) is the product of the transgression occurring in the middle of the Cretaceous Period, during the Aptian Age. It is known to have a thickness of approximately 180 metres in the Kisbér area. The products of continental sedimentation (Csehbánya, Ajka and Halimba Formations), preceding the Late Cretaceous transgression, have been revealed by the Duka, Dabrony, Ukk, and Pápakovácsi wells. In the course of transgression, the shallow-marine marl (Jákó Marl) was the first to be deposited above the terrigenous formations. As the water level rose, deep-water marl, calcareous marl (Polány Marl) was formed. The elevated surfaces of the tectonically fragmented terrain became covered by the sea in the Campanian; rudist limestone was formed on the carbonate platforms (Ugod Limestone).

Basin fill sediments

Palaeogene formations are known only in the Transdanubian Range, as well as in its western–north-western and northern forelands. From a hydrocarbon-geological point of view, neither the Eocene nor the Oligocene formations play a significant role. Predominantly sedimentary rocks, and subordinately volcanics contributed to the Neogene basin filling sequence. The basin fill formations unconformably overlie the older basement formations.

In the Early Miocene the continental terrain of the Danube Basin and the area of the Eastern Alps were connected. At this time (and maybe at the beginning of the Middle Miocene) hundreds of metres of thick, coarse-grained clastic beds of fluvial origin were deposited in the western part of the region (the Ligeterdő Formation). At the same time, continental sedimentation took place in the eastern and south-eastern part of the area (Somlóvásárhely Formation).

In several well sections, the eroded surface of the older rocks is locally overlain by very thick, terrigenous breccia and conglomerate succession, characterised by a clayey-silty matrix; this forms the basal formation of the Neogene succession. Red coloured claystone and sandstone layers can also be observed in the sequence. The thickness of the formations may even exceed 300 metres (Mosonszolnok Msz–1, Rajka Raj–1 wells). Their age is not clear, and some authors have classified them into the Karpatian (BALÁZS 1986, KŐRÖSSY 1987). (Note: one must distinguish between the terrestrial formations referred to above and the abrasion conglomerate and gravel layers occurring at the base of the marine Badenian beds.)

Transgression reached the area from the south at the beginning of the Badenian. The Badenian formations are products of different sedimentary environments, which were closely connected to each other. Palaeogeographic variability of the area is indicated by the several different facies. Both their thicknesses and depths within the succession vary. The Early Badenian cycle-starting marine, littoral abrasion gravel, conglomerate, shallow-marine sand and sandstone (Pusztamiske Formation) are widespread in the western, north-western margin of the Transdanubian Range. The thickness of the beds in the Danube Basin area is approximately 100–150 metres. The Pusztamiske Formation may laterally interfinger with the Lajta Limestone Formation, and — towards the inner parts of the basin — with the fine-grained siliciclastic sediments of

the Tekeres Schlier Formation. Shoreline reef facies is represented by the different lithologies of the Lajta Limestone Formation (calcareous algal limestone, calcareous sandstone, and calcareous marl) starting frequently with basal conglomerate; in the basin area they are connected to the basement highs (Pinnye, certain parts of the Mihályi Ridge, Ikervár). They are extensive on the margins, and can be studied on the Fertőrákos–Ruszt Hills and on the surface in the western, north-western foreland of the Transdanubian Range. The thickness of the "Leithakalk" is mostly some tens of metres, with a maximum thickness of about 100 m. Its sedimentation encompasses the entire Badenian stage. It has marine facies of normal salinity. Regarding the fine-grained siliciclastic marine formations, the areal extent of the Tekeres Schlier Formation is characteristic of the southern, south-eastern part of the Danube Basin. It consists of nearshore, open-water, grey, fine-grained sandy silt, argillaceous marl, micaceous sandstone, and glauconitic sandstone. Based on biostratigraphic studies, it was formed in the Early Badenian (SELMECZI et al. 2004, GYALOG, BUDAI ed. 2004). Its palaeogeographic connections can be traced towards the Zala and Dráva Basins. Its thickness is approximately 100–200 metres in the Danube Basin. In the submarine depressions, dark grey and grey clay / argillaceous marl were deposited during the Early Badenian (Baden Formation) (RÖGL 1998; NAGYMAROSY 1985; BOHN-HAVAS et al. 1987; HÁMOR 1996, 1997). Its thickness exceeds 500 metres (577 m in the Tét–3 well). It can be seen on the surface in the Sopron Mountains. Tuff intercalations associated with the middle rhyolite tuff explosion, and can also be observed in the Lower Badenian sequence. The shallow-neritic sandstone and mollusc- and foraminifer-bearing argillaceous marl with tuffite intercalations (Szilágy Clay Marl Formation) was formed in the younger periods of the Badenian. In many areas it overlies the Early Badenian fine-grained siliciclastic sequence, and is overlain by the Sarmatian argillaceous marl. Due to the lithological similarity, the determination of the lower and upper boundaries is possible only by biostratigraphic studies, so the exact thickness of the Szilágy Clay Marl is unknown at several locations. Sometimes its thickness may reach several hundreds of metres. It laterally interfingers with the Rákos Member of the Lajta Limestone (the so-called "Upper Leithakalk").

During the Sarmatian, the Danube Basin subsided to variable degrees: at the margins, with successions only some tens of metre thick; in the rapidly sinking basinal areas (for instance Csapod Trough), several hundred metre-thick successions were deposited. Sarmatian sediments are known only sporadically in the Mihályi Ridge, since a significant part of the ridge may have been on the surface at this time, dividing the sedimentary basin into two parts (BALÁZS 1986). The Sarmatian stage in the basin is represented basically by the brackish-water, fine-grained siliciclastic sediments of the Kozárd Formation. Sand–sandstone, calcareous marl and tuffaceous clay intercalations occur in the open-water, argillaceous marl – silty clay marl succession. Where there are continuous successions, the formation conformably overlies the Badenian beds. In some cases it unconformably rests on formations older than the Late Badenian. Locally it develops gradually from the sediments of the Tinnye Formation (Cell. ÉK–1), and laterally interfingers with it towards the margins. It is conformably overlain by (Middle–)Upper Miocene (Pannonian) sediments (Endrőd Formation). The maximum thickness of the Kozárd Formation in the basin area is several hundreds of metres: approximately 400 metres in the Csapod Trough; and exceeding 700 metres in the surroundings of Bősárkány (BALÁZS 1986). Its maximum thickness on the margins is approximately 100 metres. The layers of the Tinnye Formation, consisting of shore face, biogenic carbonates, are subordinate in the Danube Basin. They are encountered more frequently on the basin margins only (in the vicinity of the Sopron Mountains and in the forelands of the Transdanubian Range). Their thickness is some tens of metres.

Subsidence of the sub-basins east and west of the Mihályi Ridge (of NNE–SSW direction) went on in the Early Pannonian. In the Late Pannonian the entire territory of the Danube Basin began sinking, although unevenly. More intensive subsidence occurred in the Csapod–Bősárkány trough and Győr deep zone. The subsidence of the Győr deep is still going on; at the deepest point, the total thickness of the Neogene and Quaternary successions may exceed 8 km, and in Slovakia it may even reach 10 km (HRUŠECKÝ et al. 1996). A seismic profile of Mk–1 in the NW–SE direction — crossing the area — is shown in Figure 4.1.3; the Csapod Trough can be clearly distinguished on the left side of the profile (that is, on the north-western part). Next to it, towards the SE, the Mihályi Ridge can be seen. SE of the latter the Kenyeri deep zone can be observed.

The seismic section Vcsa–24 runs to the south of the section Mk–1 in an approximately west–east direction (Figure 4.1.2) The section starts from the Sopron area in the west; from W to E it crosses the Nagycenk depression, the Pinnye high, the Csapod Trough and the northern part of the Mihályi Ridge; and E of this area the basement gradually descends.

At places at the base of the Pannonian sequence (e.g. Mihályi M–1 well) the basal conglomerate (Békés Conglomerate Formation) can be observed; it comprises the debris of the basement. The Lower Pannonian succession starts with the calcareous marl and marl beds of the Endrőd Marl Formation of open-marine facies ("Lower marl level"). Farther up there is a consecutively transition into clay marl. In certain successions (e.g. Pér–1, Gönyü–1) a continuous transition from the Sarmatian into the Pannonian can be assumed. In the higher parts of the formation siltstone–sandstone stripes of the distal parts of the turbidites can be observed, suggesting a continuous transition into the Szolnok Formation. The latter is made up of alternating layers of sandstone, siltstone and clay marl – marl of turbiditic origin, formed in deep-water environment. It might be several hundred metres thick (570 m in the Bősárkány Bő–1 well, 410 m in Csapod Cs–1). The thickness of the dark grey clay marl succession of the Algyő Formation — which was deposited in the underwater slope environment — is 100–500 metres. Its stratigraphic overburden rock is the Újfalu Formation. Towards the margins of the Transdanubian Range the pinching-out of the basinal formations can be observed.

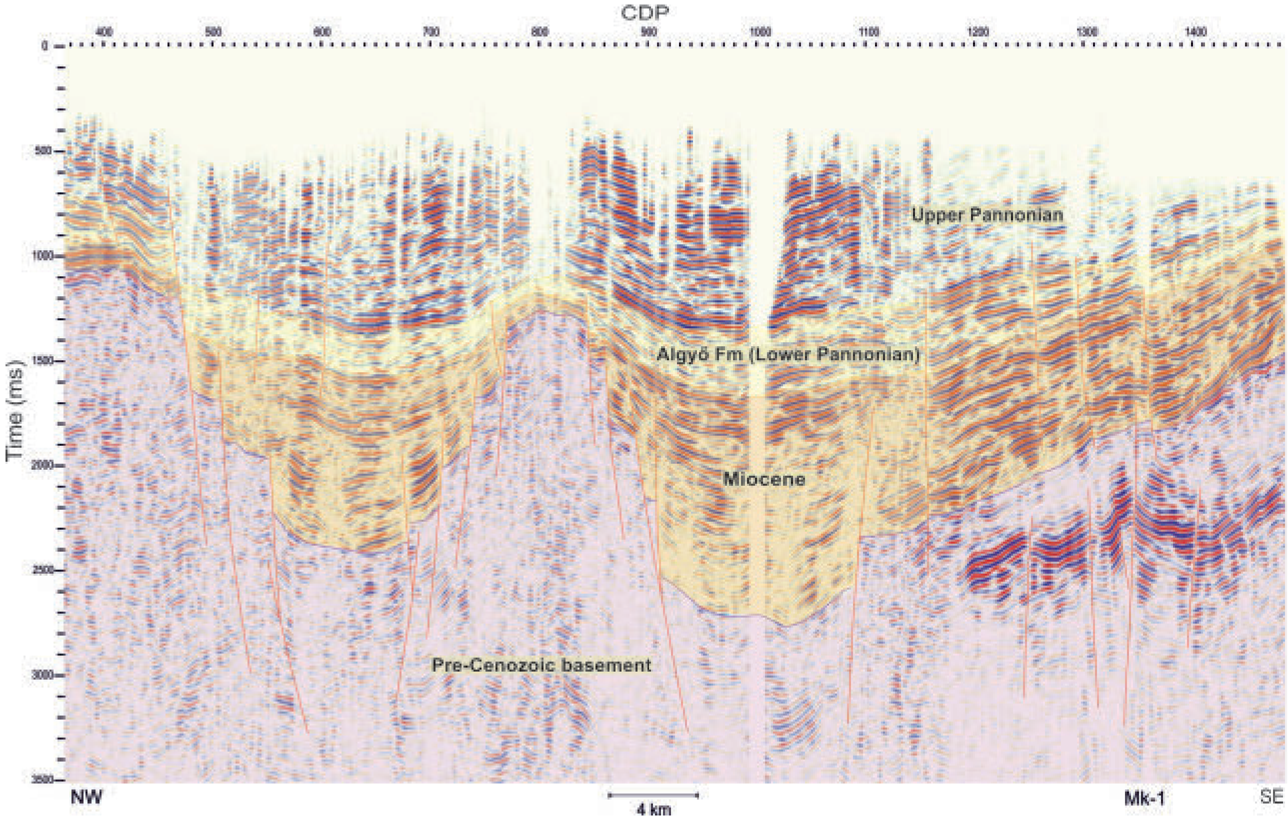


Figure 4.1.3. Seismic section Mk-1 of NW-SE direction crossing the area
From left to right: Csapod Trough, Mihályi Ridge and the Kenyeri deep zone

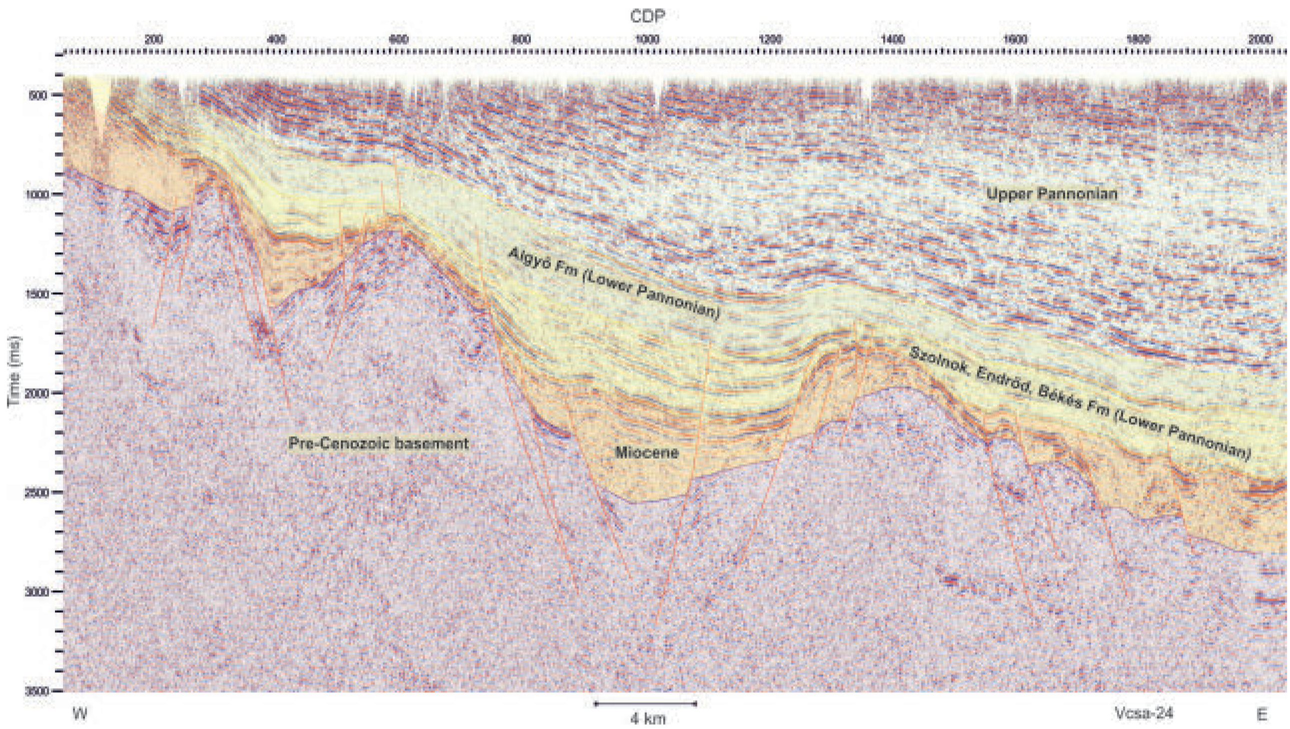


Figure 4.1.4. Seismic section Vcsa-24 of approximately W-E direction, crossing the Little Hungarian Plain / Danube Basin area
The Csapod Trough can be seen in the middle of the profile, the Pinnye high is to the left of it, and Mihályi Ridge is to the right of it

Pannonian formations overlie transgressively the older formations at the basin margins (in the surrounding of Nagyigmánd, Kisbér, Bakonyszombathely, Gic, etc.) in the transgressive manner. In the lower part of the succession, one finds the sediments of the Kisbér Gravel Member of abrasion facies and the clay marl and siltstone beds of the Szák Clay Marl Member. The Szák Formation is overlain by the sandstone (–siltstone – clay marl) succession of the Újfalu Formation of regressive, shallow-lake–delta facies. Its thickness is usually 100–300 metres, but greater depths are known as well (e.g. 420-metre thick sediments in the Győr K–107 well). Its developments at the margins, i.e., in the Transdanubian Range forelands (Somló and Tihany Members), are characterised by lesser thicknesses and rarer sedimentary cycles. The fine-grained siliciclastic sediments and calcareous clay and lignite layers (the former Torony Lignite Formation) — known from the wells in the Szombathely and Dör area — also belong to the Újfalu Formation. The Zagyva Formation, formed of the alternating layers of fluvial and lacustrine sand, sandstone and clay, is widespread. It usually overlies the Újfalu Formation, and can be detected in the eastern part of the area, covering the Szák Clay Marl (Nagyigmánd B–29 well). Similar Quaternary sediments lie above it. The Zagyva Formation is some hundred metres thick but in places is more than 500 metres thick (e.g., 677 meters in the Mosonszentjános Mos–1 well; 565 meters in the Csapod Cs–1 well and nearly 1,000 meters in the Ikervár Ike–5 well) (GeoBank well geological database of the Mining and Geological Survey of Hungary).

In the wells drilled at Mihályi and Dör the Hanság Formation was distinguished; their successions are mostly composed of alternating layers of fluvial and lacustrine clay and sand. Occasionally, it comprises lignite stripes, basalt veins, tuff traces and gravel layers (Németh 1996). It is underlain by the Újfalu Formation, the Tapolca Basalt Formation and the Torony Lignite Member of the Újfalu Formation. It is overlain by Quaternary sediments. Its thickness in the successions referred to above is 50–223 metres.

Based on the geological investigation of Pásztori and Szany wells two kinds of volcanic activities have become known: an older trachytic and the younger basaltic/doleritic type. The trachytic volcanism is more significant. Its centre of eruption was found in the Pásztori area (Pásztori Trachyte Formation). Trachyte – lapilli tuff can be observed 20 km to the north and to the south-east of the eruption centre (Balázs 1986). It forms intercalations in the Endrőd Marl Formation in a thickness of 40 metres in the Tét–1 well. The age of the Pásztori Trachyte Formation ranges from Early Badenian to Early Pannonian (Németh, Hámor 1996). It can be assumed that the volcanic eruption occurred at the Sarmatian–Pannonian boundary. There is a close correlation between the beginning of the intensive subsidence of the Győr Basin along the Rába Line and the renewal/dilatation of the deep fracture. Younger, slightly alkaline dolerite dykes penetrate the trachyte, while lava flow can be detected in the upper levels (Tapolca Basalt Formation) (Balázs 1986).

During the Quaternary, fluvial environment was predominant in the region and the deposition of alluvial fans took place; in the stagnant aquatic environment lacustrine and paludal facies were predominant. Pleistocene loess, sandy loess, loessy sands are typical especially in the forelands of the mountains (Kisbér, Bakonyszentlászló, Veszprémvarsány, Bábolna). The thickness of the Quaternary sediments significantly exceeds 100 metre at certain places.

An overview of hydrocarbon geology

On the western–north-western side of the Rába Line, the Ikervár–Répcelak–Mihályi regional natural gas accumulation zone runs in a SW–NE direction for several tens of kilometres, associated with natural gas and carbon dioxide gas occurrences. Gas reservoirs were formed mainly in dome structures situated above the basement highs consisting of Early Palaeozoic rocks. They can be found predominantly in the Pannonian, subordinately in the Badenian sandstone and limestone layers, and lastly in basement complex reservoirs. This series is dominated by carbon dioxide gas (the largest CO_2 reservoirs of the country can be found here), but high-quality hydrocarbon gas reservoirs were also formed in higher horizons (Juhász, Kummer ed. 1997). Small natural gas accumulations were formed east of the Rába Line, in the eastern part of the Danube Basin, and in the area stretching up to the foot of the Transdanubian Mountains (Tét, Celldömölk and Pásztori area, Figure 4.1.5).

Source rocks

In the Danube Basin, Middle Miocene and Lower Pannonian fine-grained clastic sediments can be taken into account as potential source rocks. Additionally, in the eastern part of the basin, certain formations of the pre-Cenozoic basement can also be considered as source rocks (Figure 4.1.6).

In regard to the rocks of the Palaeozoic basement in the Mihályi High area and its vicinity, the value of the vitrinite reflectance (R_0) is 4–6%, whereas this value is approximately 0.6% for the Miocene sediments. The latter reached the top of the oil generation zone at a depth of 2.6–2.9 km (Koncz 1983). Based on carbon isotope ratios, the methane (CH_4) in the carbon dioxide rich natural gas occurrences could have originated from the Neogene source rocks. On the base of their composition, such gases and condensates could have originated from the Neogene sediments when carbon dioxide generation took place in the early and middle period of oil generation (Koncz, Etler 1994). Hydrocarbons discovered in

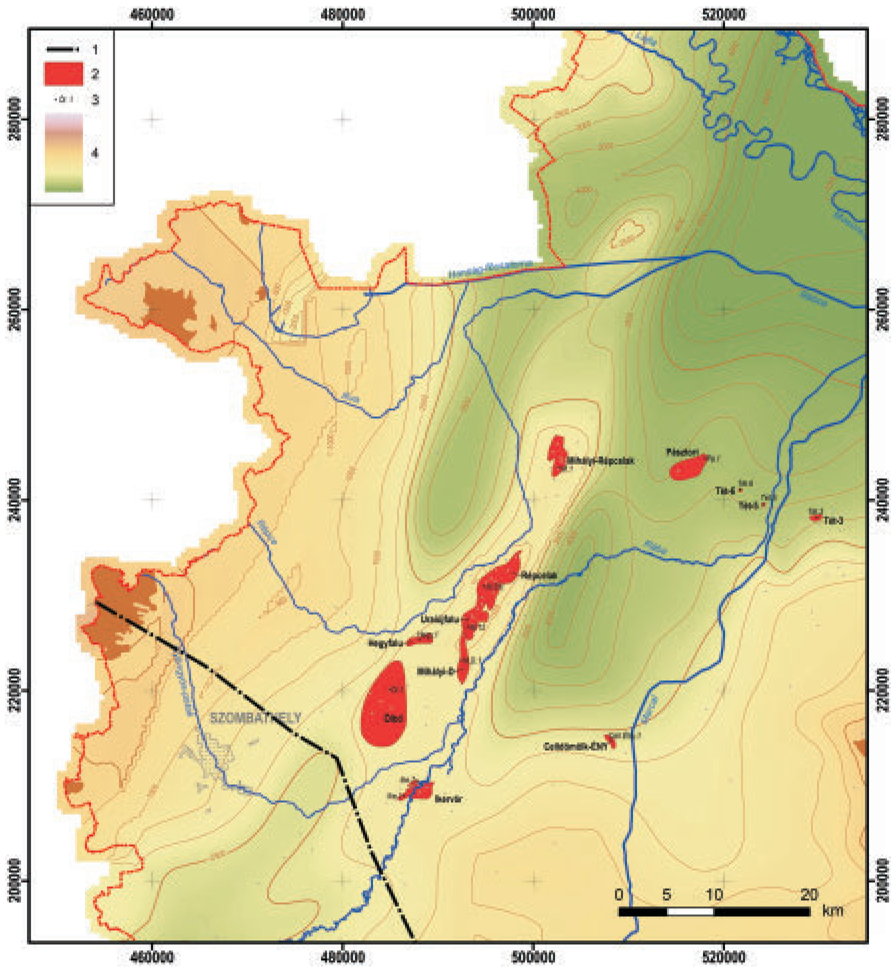


Figure 4.1.5. Location of hydrocarbon fields in the Danube Basin area
1. Boundary of the basin, 2. Conventional field, 3. Discovery wells of the fields, 4. Depth of the pre-Cenozoic basement

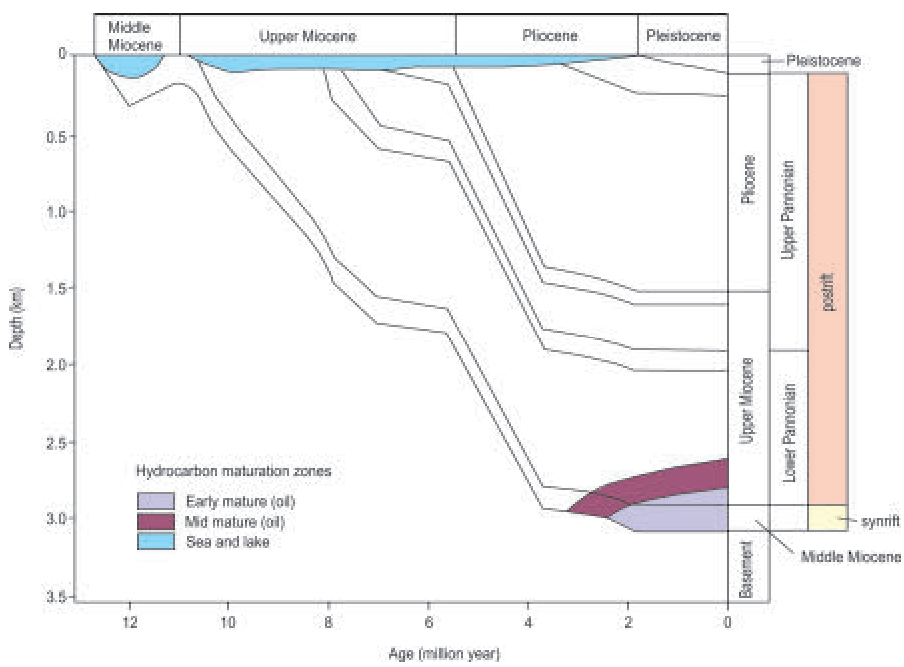


Figure 4.1.6. Burial history of the Little Hungarian Plain (Danube Basin) area and the hydrocarbon generating zones (adapted from DOLTON 2006)

the Mihályi High area could have been generated in the Csapod deep zone, where Middle Miocene and Lower Pannonian pelitic sediments were deposited in great thickness (Bokor et al. 1990, Kőrössy 1987, Mészáros et al. 1974). Neogene source rocks situated at greater depths could have reached the oil and partly the gas generation zone in the Late Miocene, and during the subsequent subsidence of the basin. Fractures — formed as the consequence of the differentiated post-rift subsidence — could have supported migration routes for fluids towards the basement highs and the domes above, as well as in the direction of the coarse-clastic layers pinching out in the limbs of the elevations.

Porosity of the potential source rocks in the Danube Basin is greater than that of the corresponding rocks in the Great Hungarian Plain, because the Danube Basin was the accumulation area of the eroded, coarse grained clastic sediments transported from the Alps and the Carpathians. It can be assumed that the organic matter could have been enriched to a lesser extent here because of the higher proportion of coarse clastic sediments (and hence, shallower water depth) — as happened in the "sediment-starved", distal from the basin-edge parts of the Pannonian Basin (Mattick et al. 1996). In other words, one must assume poorer-quality source rocks. It can also be assumed that the CO_2 gases in the Danube Basin were not generated from these source rocks, but as the result of the metamorphism of the Palaeozoic carbonates of the Upper Austroalpine basement rocks (Kovács Zs. ed. 2013). According to Kőrössy (1987), the presence of these rocks of the metamorphic basement is unfavourable from a hydrocarbon-geological point of view; its original organic matter must have become too matured, with the overlying coarse clastic sediments representing oxygene-rich continental–near-shore sedimentary environments. The lower, organic-rich source horizons of the Lower Pannonian succession are also absent.

Besides the Neogene (Badenian–Sarmatian and Lower Pannonian) pelitic sediments which count as potential source rocks in the eastern basin part of the Danube Basin, some organic-rich Mesozoic formations must also be taken into account. Such formations include the Middle Triassic, basin-facies, bituminous Felsőörs Limestone Formation, which might reach a thickness of 100 m. The Veszprém Marl Formation is also listed as source rock, because it is the sediment of the basin dissected by carbonate platforms, and its thickness might be hundreds of metres. Its general extension can be assumed in the south-eastern part of the Danube Basin under the Main Dolomite. It is known from wells deepened in the Győrszemere, Gönyü, Bakonyszücs, Bakonyszentlászló, Mesteri areas. Total organic carbon content (TOC) of the Veszprém Marl is in the range of 3.4–34.3 mg/g. TOC in the Bakonyszücs–I well is from 1.9 to 5.6%, in the Bakonyszücs–3 well from 0.5 to 6.8%. Based on the analysis of the Döbrönte–I well core and cutting samples, it can be assumed that the Veszprém Marl has low levels of thermal maturity. Samples contain gas-generating kerogen with very low hydrocarbon potential (Turtegin et al. 2004, Velledits, Horváth 2011). The pelagic argillaceous marl, marl, calcareous marl layers of the Kössen Marl Formation are known in surface–near-surface positions in considerable thicknesses, in the north-western areas of the Keszthely Mountains (south-western edge of the Transdanubian Range). It thus plays a subordinate role in the Danube Basin as a source rock. The Jákó Marl Formation is formed of grey argillaceous marl, marl, calcareous marl, with a maximum thickness of not more than 100 m. Considering samples taken in the Dabrony–Celldömölk–Vinár area from a depth of 2,000–3,000 metres, the vitrinite reflectance (R_0) values vary between 1.1 and 1.26%, in other words, Cretaceous formations already reached the oil generation zone (Turtegin et al. 2004).

Potential Neogene source rocks (Badenian – Lower Pannonian pelitic sediments) reached the depth sufficient for maturity during the last couple of million years due to the post-rift subsidence, which is still ongoing in the central part of the basin. The low amount of discovered hydrocarbons might be related to the low organic carbon contents of the source rocks and the unfavourable trapping conditions.

Based on the analysis of samples taken from the Nagygörbő–1 well south of the Northern Transdanubia – Little Hungarian Plain area, the Tekeres Schlier Formation of Middle Miocene (Early Badenian) age can be considered an excellent hydrocarbon generating source rock (Badics, Vető 2012). According to results of the bituminite content and vitrinite reflectance analysis carried out on samples from the Celldömölk area, the early oil generation zone in the Celldömölk–Vinár area can be found at a depth of 1,500–2,100 metres. The pre-Pannonian Miocene sediments and the Lower Pannonian calcareous marl level (Tótkomlós Marl Mb) occur in this zone. The average level of organic matter content is between 2.17 and 6.62 mg/g. The main oil generation zone is found at a depth between 2,100 and 2,450 metres, and comprises the sediments of the Upper Cretaceous Polány Marl. The average organic matter content is in a range of 1.02–4.51 mg/g. The wet gas generation zone is located below 2,450 m (Ugod Limestone and Jákó Marl level), with an average value for the organic matter-contents in a range of 1.11–1.84 mg/g. The maturity zone boundaries in the Neogene – Upper Cretaceous sediments can be found deeper, attributable to the possible cooling effect of karst water flow in the carbonate rocks of the Mesozoic basement (Bernáthné et al. 1997e). Geochemical analysis of rock samples from the Tét area suggests that most of the organic matter in the Neogene sediments here could be gas generating (Bernáthné et al. 1989).

Hydrocarbons in the Celldömölk field were generated most likely in the Kenyeri deep zone (ESE of Mihályi High) of the Danube Basin, and got to stratigraphically–lithologically closed traps by migration towards the south-west. Hydrocarbons of the Tét and Pásztori occurrences may easily originate from the Kenyeri or the Győr deep zone (NE of Mihályi High) areas (Bernáthné et al. 1989, 1997e; Juhász, Kummer ed. 1997).

Migration

In the case of the occurrences discovered in the Mihályi High area, the migration took place from the surrounding deeper basin parts as feeding areas towards the higher elevations. In the area of the western sub-basin (Csapod Trough) of the Danube Basin, the migration might have happened primarily along the unconformity surface, from west to east, between the Early Palaeozoic basement and the overlying Middle Miocene successions. (BOKOR et al. 1990). The migration might also have been affected by Lower Pannonian delta slope sediments (KONCZ, ETLER 1994) and fractures which came into being due to the differential post-rift subsidence (KOVÁCS ZS. ed. 2013).

In the eastern part of the Danube Basin, hydrocarbons probably migrated from the Kenyeri deep zone into the Badenian natural gas reservoir of the Celldömölk field as they moved towards the SE. The Mesozoic carbonate rocks, the unconformity surfaces and tectonics zones should be considered as the pathways for migration (BERNÁTHNÉ et al. 1997e). In the occurrences formed at the boundary of the Transdanubian Range and the Danube Basin (i.e., Tét reservoirs) the traps were filled up through migration towards the basin margins (JUHÁSZ, KUMMER ed. 1997).

Reservoir rocks

Potential reservoir rocks of the Danube Basin include the following (MÉSZÁROS et al. 1974, 1975a, b, 1979; BERNÁTHNÉ et al. 1989, 1997e; JUHÁSZ, KUMMER ed. 1997; HORVÁTH, TARI 1999; TARI, HORVÁTH 2006; TURTEGIN et al. 2004 and VELLEDITS, HORVÁTH 2011, Figure 4.1.7):

— Early Palaeozoic (Variscan) basement metamorphic rocks (Hegyfalu, Ikervár, Mihályi–Répcelak fields),

— Middle Triassic dolomite (Aszófő Dolomite Formation) at the parts with voids and fractures,

— Upper Triassic carbonates (Main Dolomite and Dachstein Limestone) fractured, karstified parts,

— Upper Cretaceous (Senonian) rudist limestone (Ugod Limestone Formation),

— Upper Cretaceous Inoceramus-bearing marl (Polány Marl Formation): sandstone beds,

— Middle Miocene (Badenian) green sandstone (Celldömölk field),

— Middle Miocene (Badenian) "Leithakalk" beds: conglomerate, calcareous sandstone, limestone (Lajta Limestone Formation) (Ikervár, Mihályi–Répcelak fields),

– Middle Miocene (Badenian) argillaceous marl and sandstone (Tét–3 reservoir),

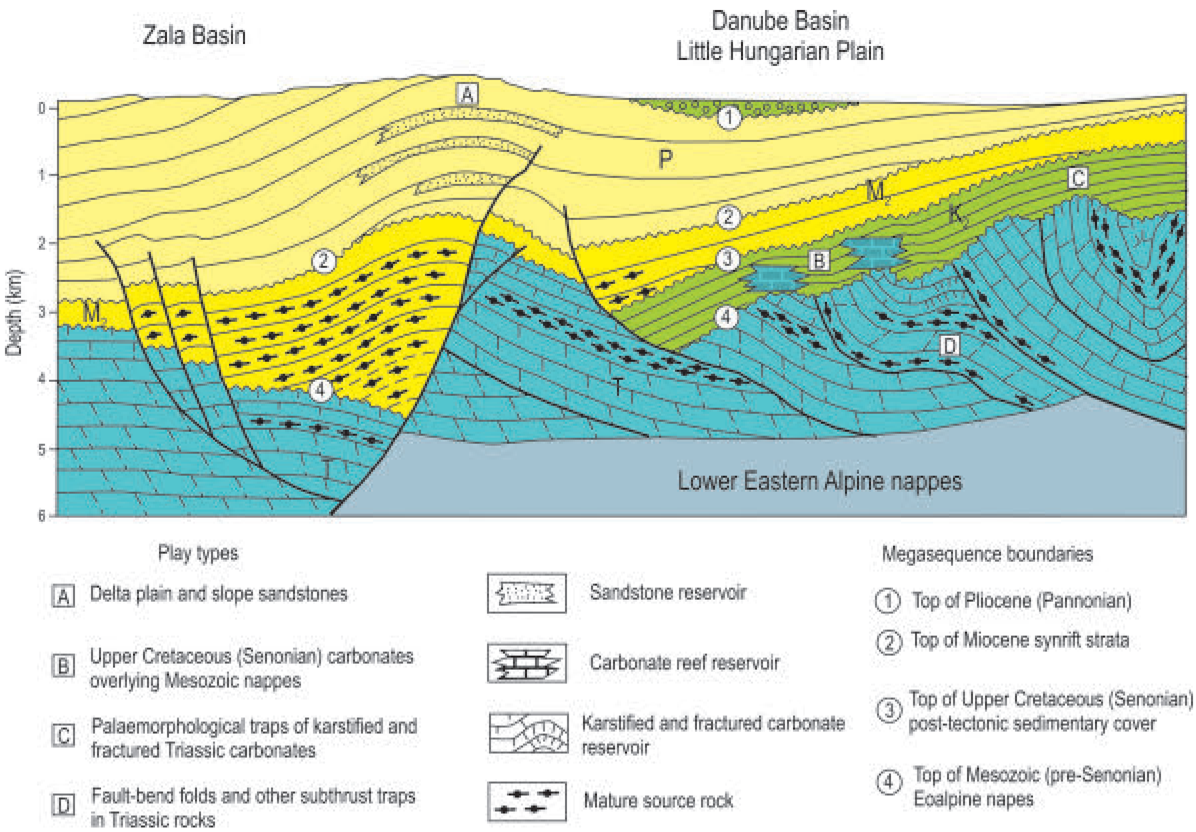


Figure 4.1.7. Theoratical profile of the hydrocarbon systems of the Zala Basin and the Danube Basin area (adapted from HORVÁTH, TARI 1999, TARI, HORVÁTH 2006)

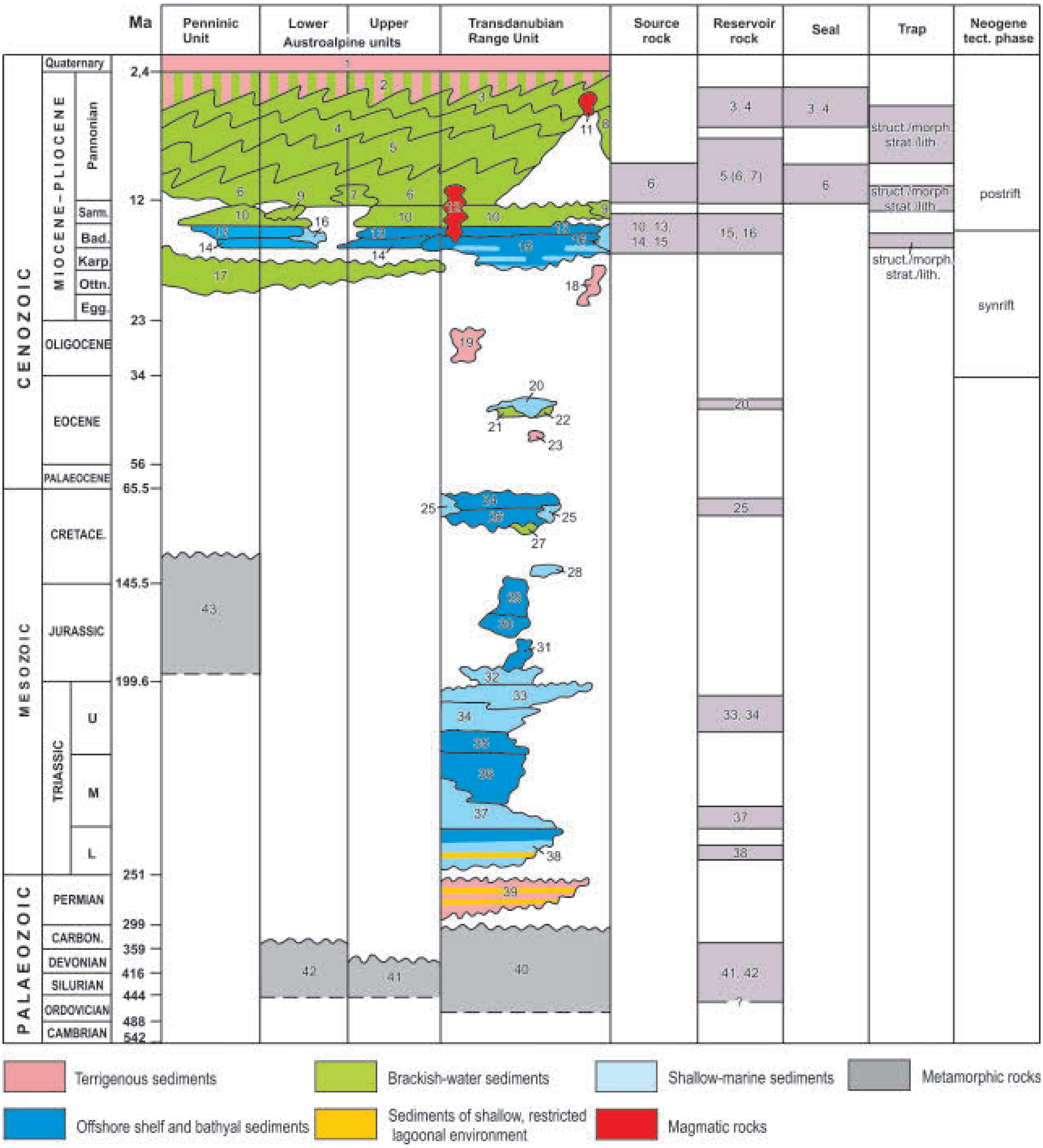


Figure 4.1.8. Lithostratigraphic column of the Northern Transdanubia – Little Hungarian Plain (Danube Basin) area and the elements of hydrocarbon systems

1. Quaternary sediments (0–700 m), 2. Zagyva and Hanság Formations and Torony Member of the Újfalu Formation undivided, (0–800 m), 3. Újfalu Fm, Somló and Tihany Members of the Újfalu Fm undivided, (50–1200 m), 4. Algyő Fm (100–500 m), 5. Szolnok Fm (100–600 m), 6. Endrőd Fm (0–500 m), 7. Békés Conglomerate Fm (0–40 m), 8. Szák Fm Szák Clay Marl and Kisbér Members undivided (0–150 m), 9. Tinnye Fm (0–110 m), 10. Kozárd Fm (0–650 m), 11. Tapolca Basalt Fm (0–150 m), 12. Pásztori Trachyte Fm (0–700 m), 13. Szilágy Clay Marl Fm (0–500 m), 14. Baden Clay Fm (0–600 m), 15. Pusztamiske Fm – Tekeres Schlier Fm, undivided (0–300 m), 16. Lajta Limestone Fm (0–100 m), 17. Ligeterdő Fm (0–400 m), 18. Somlóvásárhely Fm (0–250 m), 19. Csatka Fm (0–350 m), 20. Szőc Limestone Fm (0–60 m), 21. Darvastó Fm (0–10 m), 22. Kisgyón Fm (<50 m), 23. Gánt Bauxite Fm (0–15 m), 24. Polány Marl Fm (0–600 m), 25. Ugod Limestone Fm. (0–300 m), 26. Jákó Marl Fm. (0–400 m), 27. Csehbánya–Ajka Fm., undivided (< 200 m), 28. Tata Limestone Fm. (0–200 m), 29. Szentivánhegy Limestone Fm (0–10 m), 30. Pálihálás Limestone Fm (0–50 m), 31. Pisznice Limestone Fm (0–15 m), 32. Kardosrét Limestone Fm (0–51 m), 33. Dachstein Limestone Fm (0–150 m), 34. Main Dolomite Fm (>800 m), 35. Veszprém Marl Fm (0–1000 m), 36. Middle-Triassic basin facies carbonates (Felsőörs Limestone, Buchenstein and Vászoly Fms) (0–200 m), 37. Middle Triassic shallow-marine carbonates (Aszófő Dolomite, Megyehegy Dolomite, Iszkahegy Limestone, Tagyon Limestone Fm) (0–500 m), 38. Lower Triassic fine-grained siliciclastic and carbonate sediments (Csopak Marl, Hidegkút, Köveskál Dolomite, Arács Marl Fms, 0–300 m), 39. Balatonfelvidék Sandstone and Tabajd Anhydrite Fms, undivided (0–400 m), 40. Weakly metamorphosed rocks: Lovas Slate and Nemeskolta Fm), 41. Weakly metamorphosed rocks: Mihályi Phyllite, Sótony Metavolcanite and Bük Dolomite Fm, 42. Metamorphic crystalline rocks: Sopron Crystalline Schist Group, Fertőrákos Crystalline Schist Group, 43. Weakly metamorphosed rocks (Kőszeg Quartz Phyllite, Velem Calcareous Phyllite, Vashegy Serpentinite and Felsőcsatár Green Schist Fms). Trapping: struct/morph: traps formed above the structurally and morphologically developed basement structure; strat/lith: stratigraphic and lithologics; diszk: stratigraphic trap formed along an unconformity surface

– Middle Miocene (Badenian) argillaceous marl, sandstone and volcanics (Pásztori Trachyte) (Tét–6 reservoir),

– Middle–Upper Miocene volcanics (Pásztori Trachyte Formation) (Pásztori, Tét–5 reservoirs),

– Pannonian sandstones (Szolnok Sandstone Formation — Mihályi-South, Mihályi–Répcelak, Pásztori; Újfalu Sandstone Formation — Mihályi–Répcelak, Pásztori, Uraiújfalu fields).

The theoretical column representing formations in the Danube Basin area and essential elements of the hydrocarbon system are shown in Figure 4.1.8. One of the main hydrocarbon reservoir horizons is the fractured, weathered, brecciated top zone of the Palaeozoic basement, which has a porosity level of 2–20% (JUHÁSZ, KUMMER ed. 1997). The porosity of the basement reservoir at Ikervár is 1.5% (VÖLGYI et al. 1985).

In the Hegyfalu field, trapping took place along the unconformity surface; the reservoir developed in the metamorphic basement and stores carbon dioxide gas. According to BOKOR et al. (1990), a Miocene – Early Palaeozoic multiple reservoir was formed here, sealed by an impermeable Lower Pannonian marl.

In regard to the CO_2 gas reservoir of the Mihályi basement horizon in the Mihályi–Répcelak field, the uppermost part of the Early Palaeozoic sequence together with the Upper Miocene (Lower Pannonian) basal conglomerate (Békés Formation) has a reservoir complex with 3.3% porosity (VÖLGYI et al. 1985).

The multiple carbon dioxide gas reservoir of the Ölbő field comprises the Early Palaeozoic basement rocks and the Miocene lithothamnian limestone (Lajta Limestone Formation) in a stratigraphic trap associated with the unconformity zone between the two formations. The reservoir porosity is 8% (VÖLGYI et al. 1985).

The Mesozoic formations and the Upper Triassic carbonates (Main Dolomite and Dachstein Limestone Formation) might possess excellent reservoir properties, due to their secondary porosity developed as a result of the subsequent tectonic impacts and multiple karstification. Neither, however, do the reservoir parameters of the Upper Cretaceous (Senonian) and rudist limestone (Ugod Limestone Formation) similar to the Upper Triassic carbonates (TURTEGIN et al. 2004). The Middle Triassic, fractured, cellular dolomite (Aszófő Formation, Celldömölk. ÉK–1 well), the Upper Triassic Main Dolomite (Da–1 well), and the Upper Cretaceous rudist limestone (Ugod Limestone Formation), which store water, can be qualified as reservoir rocks in the Celldömölk field area (BERNÁTHNÉ et al. 1997).

The average porosity of the Badenian green sandstone reservoir of the pre-Pannonian Miocene reservoir of Celldömölk occurrence is 12%. (BERNÁTHNÉ et al. 1997). The porosity of the Badenian natural gas containing calcareous sandstone and pebbly sandstone conglomerate (Lajta Limestone Formation) reservoir of the Ikervár–2 well is 10% (VÖLGYI et al. 1985).

The reservoir in the Tét–3 well is a small Badenian sandstone lens, with a porosity of at least 14–15% (BERNÁTHNÉ et al. 1989). In the Tét–5 reservoir the porosity of the Pásztori Trachyte is 10.5% (BERNÁTHNÉ et al 1989).

The Pannonian sandstones possess excellent reservoir properties, and their porosity exceeds 20% (Upper Pannonian sandstones porosity values are in a range of 19–25%) (VÖLGYI et al. 1985, BERNÁTHNÉ et al. 1989, BOKOR et al. 1990).

Seal rocks

Clays and argillaceous marls overlie the reservoirs, are impermeable under hydrostatic pressure conditions, and can be considered seals. These rocks may be open-marine marls or calcareous marls. Vertical closures of reservoirs, formed in the Badenian lithothamnium beds ("Lajta Limestone") and in the Lower Pannonian sandstone, is allowed by the overlying impermeable Pannonian layers. Lateral closures are developed due to lithological changes or faults. Even the several metres thick argillaceous marls and the impermeable rock bodies — separating the sandstone layers — behave like seals within the Pannonian sequences.

Trapping

The post-rift evolution has not encouraged trapping in the Danube Basin: except for the Mihályi High, there are no known elevated zones, no blocks in the region which could have formed more serious structural closures. In the eastern part of the Danube Basin, there are tilted sequences with slight dipping constantly ascending from the Győr–Kenyeri deep zone towards the edges (inverted at the rim of the Transdanubian Range). Because of the lack of known capable structures, neither does it now seem that any considerable amount of hydrocarbon could have accumulated in the good porosity basement carbonates (KOVÁCS ZS. ed. 2013). For instance, the south-eastern part of the Danube Basin with Mesozoic basement rocks is one of the most favourable areas from the point of view of hydrocarbon generation, but in a significant part of this area, there are structures open to the south-west which might have allowed the seepage of a large part of the potentially accumulated hydrocarbons (KŐRÖSSY 1987).

The following trap types are typical for the Danube Basin area: 1. traps formed by tectonic closure or lithological changes (Uraiújfalu, Répcelak reservoirs); 2. stratigraphic and/or morphological traps related to unconformity surfaces (Hegyfalu, Ikervár, Mihályi-Répcelak, Ölbő); 3. lithologic trap developed in a Neogene pseudo-dome (Ikervár); 4. pseudo-anticlines (Pásztori) formed above a volcanic body (Pásztori Trachyte Formation); 5. lithological trap at the top of the volcanic body (Tét–5); 6. traps formed due to lithological changes and lithologic traps (Répcelak mixed gas, Celldömölk, Mihályi-South Lower Pannonian and Tét–6 reservoirs); 7. combined stratigraphic and lithologic trap (Tét–3 well reservoir).

Hydrocarbon and carbon dioxide natural gas occurrences in the Northern Transdanubia – Little Hungarian Plain (Danube Basin) area

For the most part, the data characterising the discovered reservoirs (hydrocarbon composition, calorific value, etc.) basically originated from the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ); in other cases, the source is indicated.

Celldömölk North-west (Celdömölk-ÉNy). This natural gas field was discovered by the Cell.ÉNy–1 well in 1986. In the deeper parts of the Middle Miocene Badenian marl beds there are two fine grained sandstone intercalations deposited between 1,940–1,952 metres below sea level. The lower, 7 metres thick layer provided hydrocarbon gas and condensate production with relatively substantial water inflow (Bernáthné et al. 1997). The hydrocarbons generated probably in the Kenyeri deep zone, migrated in a south-eastern direction into the stratigraphically and lithologically closed trap (Juhász, Kummer ed. 1997). The combustible part of the free gas in the single reservoir is 82.6%, the calorific value is 36 MJ/m^3, its methane content (CH_4) is 67.8%, the carbon dioxide content (CO_2) is 6%, and the nitrogen content (N_2) is 11.4%.

Hegyfalu–Mihályi South (Hegyfalu–Mihályi-Dél). Two reservoirs are known in this field.

Mihályi South carbon dioxide gas reservoir. This was discovered by the Mihályi-Dél M.D–1 exploration well (1989) situated on the southernmost member of the Mihályi–Répcelak basement high structure series. It is a pinched out, stratigraphically–lithologically closed single reservoir in Lower Pannonian sandstone between two argillaceous marl layers, with poor water replenishment at the edges. The reservoir sandstone body is pinched out in an eastern–north-eastern direction towards the Mihályi High (Bokor et al. 1990). The gas-water contact (GWC) is found at a depth of 1,317 metres below sea level (m bsl.), the combustible part of the gas is 11.6%, and the calorific value is 4.2 MJ/m^3.

Hegyfalu carbon dioxide gas reservoir. The reservoir, with a bottom water-body formed in the sericite-quartz phyllite of the Variscan low-grade metamorphic Palaeozoic basement (Mihályi Phyllite Formation), was discovered by the Hegyfalu Hegy–1 well (1989) positioned on the larger member of a double gravity maximum of the basement. Provided it constitutes a hydraulically unified system with the overlying Miocene marl, it can be considered a Palaeozoic–Miocene multiple reservoir (Bokor et al. 1990). The GWC is at 1,747 m bsl. The combustible part of the gas is 0.48%, the calorific value is 0.2 MJ/m^3.

Ikervár. This natural gas field was discovered by the Ike–1 well in 1962. The reservoir levels include: 1. the top part of Variscan Palaeozoic rocks; multiple reservoirs in stratigraphic traps related to the unconformity zone at the boundary of the Palaeozoic basement and the Miocene (Karpatian stage?) beds, combined with lithologic changes, 2. Miocene glauconitic sandstone, gravelly sandstone, conglomerate, and lithological traps formed in a Neogene pseudo-anticline (Völgyi et al. 1985).

Ikervár–1A reservoir: In the free gas accumulation formed on the higher elevations of the Variscan basement the GWC is at 1,460 m bsl. The combustible part of the gas is 51.9%, the calorific value is 20.6 MJ/m^3, CH_4: 52.7%, CO_2: 3.2%, N_2: 45.9%.

Ikervár–1B reservoir: In the free gas reservoir formed on the deeper positions of the basement level the GWC is at 1,525 m bsl, the combustible part of the gas 31.9%, the calorific value is 14.7 MJ/m^3, CH_4: 30.9%, CO_2: 18.0%, N_2: 50.1%.

Ikervár–2 reservoir: In the free gas reservoir formed in the Middle Miocene conglomerate the gas-water contact is at 1,575 metres below sea level. The combustible part of the gas is 53.0%, the calorific value is 19.3 MJ/m^3, CH_4: 48.0%, CO_2: 1.9%, N_2: 45.1%. The C_{5+} content (hydrocarbon compounds with more than 5 carbon atomic numbers) is 3 g/m^3.

Ikervár–3 reservoir: In the free gas reservoir situated in the Middle Miocene limestone the gas-water contact is at 1432.5 metres below sea level. The combustible part of the gas is 40.3%, the calorific value is 15.8 MJ/m^3, CH_4: 37.8%, CO_2: 20.7%, N_2: 39.0%, the C_{5+} content is 14.96 g/m^3.

Mihályi–Répcelak. The field in the Mihályi and Kisfalud area was explored by the M–1 well in 1935. Carbon dioxide gas reservoirs are known in the Variscan basement rocks, and in Miocene, Lower Pannonian and Upper Pannonian reservoirs. Two reservoirs are situated in the basement, accumulated in the stratigraphic–morphological traps related to the Variscan metamorphic Palaeozoic–Miocene unconformity surface, and are multiple reservoirs. The Miocene and Pannonian levels contain single reservoirs.

Mihályi basement carbon dioxide gas reservoir: the GWC is at 1,492.5 metres bsl. The calorific value of the gas is 0.9 MJ/m^3. The combustible part is 1.2%, CH_4: 1.4%, CO_2: 98.4%, N_2: 0.4%.

Répcelak basement carbon dioxide gas reservoir: the GWC is at 1,310 m bsl, the combustible part of the gas is 6.3%, CH_4: 4.6%, CO_2: 92.4%, N_2: 1.3%.

Répcelak Miocene reservoir: carbon dioxide gas reservoir, formed in a trap related to the stratigraphic changes in the Miocene limestone-calcareous sandstone (Lajta Limestone Formation). The GWC is at 1,280 m bsl, the combustible part of the gas 1.4%, CH_4: 0.7%, CO_2: 96.2%, N_2: 2.4%.

Lower Pannonian reservoirs: Mihályi "Lower Pannonian" I, IIA and IIB reservoirs, and the Répcelak Lower Pannonian I–VII reservoirs are found in sandstone, in lithologic traps. The GWC in the accumulations is a value varying between 1,522.5 and 1,187.5 m. The combustible part of the gas is 2.4–9.8%, the calorific value is 1.7–2 MJ/m^3, CH_4: is 1.8–9.37% (Völgyi et al. 1985), CO_2: 86–95.6%, N_2: 0.6–6.4%.

Upper Pannonian reservoirs: Mihályi Upper Pannonian I–X reservoirs (two of its in level VII [A and B]) and the

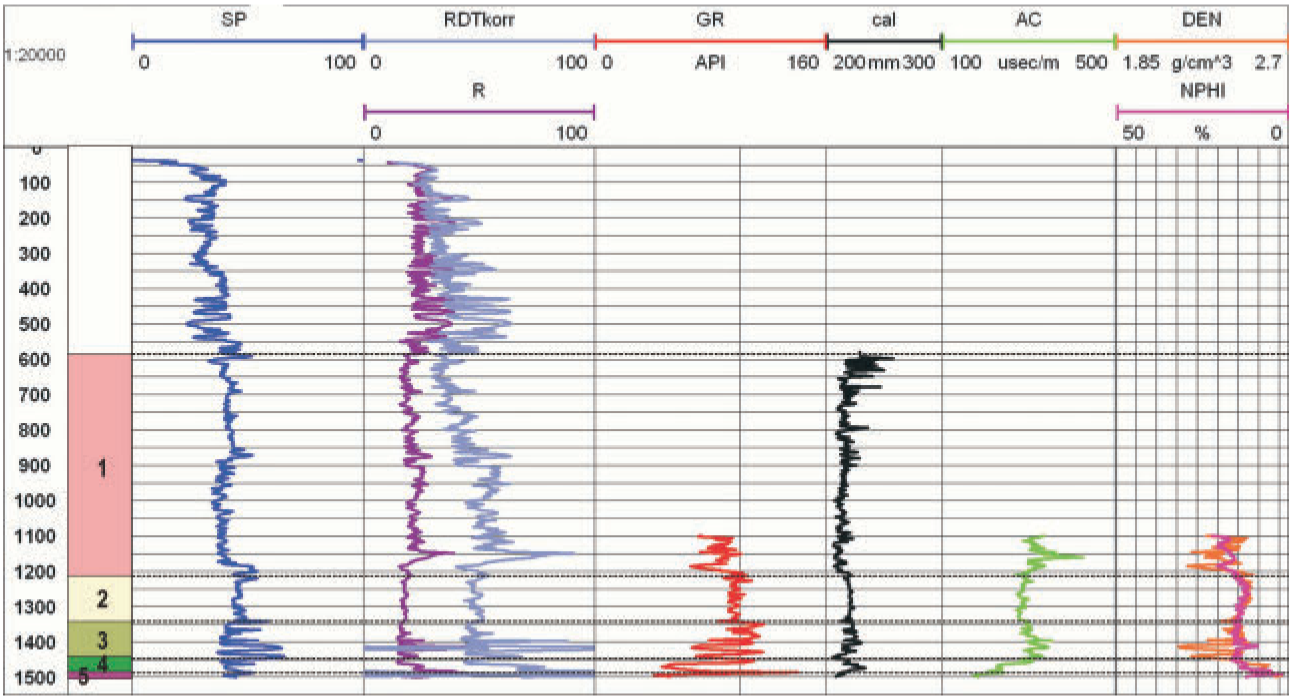


Figure 4.1.9. Geophysical well logs from the Mihályi-40 well

Legend: SP: spontaneous potential; R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log; AC: acoustic; DEN: density; NPHI: neutron-porosity log.

Stratigraphic column: 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Szolnok Fm (Lower Pannonian), 4. Endrőd Fm (Lower Pannonian). 5. Variscan basement rocks

Répcelak Upper Pannonian–I reservoir are to be found in sandstone, and shale-bearing sandstone (Újfalu Formation). The GWC-s in the reservoirs are at 1,294–1,092 metres bsl.. The combustible part of the gas is 2.5–12.9%, CH_4: 2.0–11.15%, the CO_2 content and N_2 content vary between 83.4–97%, and 0.5–3.7% (VÖLGYI et al. 1985).

Figure 4.1.9 shows sample geophysical well logs significant for the area.

Ölbő. The carbon dioxide gas occurrence was discovered by the Öl–1 well in 1964. The multiple reservoir was formed in the stratigraphic trap connected to the unconformity zone, the reservoir level is found in the top part of the metamorphic Palaeozoic rocks together with the overlying Badenian "Lajta limestone" (Leithakalk). The field lies on a relatively high basement structure of south-southwest–north-northeast axial direction. The Middle and Upper Miocene succession constitute a flat, overlying dome on the basement high. The GWC is at 1,730 m bsl, the combustible part of the gas is 2.5%, the calorific value is 1.1 MJ/m^3, CO_2: 96.2%, N_2: 1.3%.

Pásztori. The combustible natural gas and carbon dioxide gas field was discovered in 1966 by the Pá–1 well. Two free gas reservoirs are accumulated in Miocene conglomerate. The combustible part of the reservoir situated deeper is 26.6%, the calorific value is 10 MJ/m^3, CH_4: 24.4%, CO_2: 71.6%, N_2: 1.8%. The combustible part of the reservoir situated shallower is 76.8%, the calorific value is 28 MJ/m^3, CH_4: 72.1%, CO_2: 18.5%, N_2: 4.7%.

A carbon dioxide gas reservoir is situated in the Upper Pannonian sandstone (Pásztori no. 3 reservoir). The gas accumulated above the volcanic body in a Pannonian pseudoanticline structure (Pásztori Trachyte Formation). The GWC in the Upper Pannonian succession is at 1,290 m bsl. The combustible part of the gas is 1.8%, the calorific value is 0.7 MJ/m^3, CH_4: 1.5%, CO_2: 96.5%, N_2: 1.7% (VÖLGYI et al. 1985, JUHÁSZ, KUMMER ed. 1997).

Répcelak-mixed gas. This field was indicated by the M–5/b well in 1945. There are two reservoirs in the traps formed in Upper Pannonian sandstone due to lithological changes (Upper Pannonian–I and –II) (VÖLGYI et al. 1985).

Upper Pannonian–I (R-FP–I) reservoir: the GWC is at 1,068 m bsl, the combustible part of the gas is 19.1%, the calorific value is 1.8 MJ/m^3, CH_4: 17.6%, CO_2: 74.6%, N_2: 6.3%.

Upper Pannonian–II (R-FP–II) reservoir: the GWC is at 1,025 m bsl, the combustible part of the gas is 22.2%, the calorific value is 24.3 MJ/m^3, CH_4: 19.22%, CO_2: 68.6%, N_2: 9.2%.

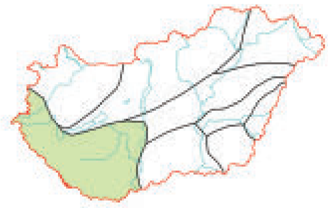
Tét. A separated reservoir was discovered by the *Tét–5* well (1984). The Tét–5 reservoir level can be found in the Miocene sequence, in the top part of the Pásztori Trachyte Formation rocks drilled between 2,856 and 3,073 metres, in a lithologic trap. The combustible part of the gas in Tét–5 is 92.4%, the calorific value is 34.2 MJ/m^3, CH_4: 85.9%, CO_2: 0.6%, N_2: 7%.

The natural gas reservoir discovered in the *Tét–6* well (1986) is situated in Badenian beds (Badenian argillaceous marl, sandstone and trachyte), in a lithologic trap (BERNÁTHNÉ et al. 1989). The combustible part of the gas is 65.3%, the calorific value is 23.1 MJ/m^3, CH_4: 47.9%, CO_2: 42.6%, N_2: 2.1%. C_{5+} content: 21.9 g/m^3.

A natural gas reservoir was discovered in 1983 by the *Tét–3* well in Miocene (Badenian) sandstone. (Bernáthné et al. 1989). The gas was accumulated in a small size Badenian sandstone lens, in a combined stratigraphic and lithologic trap (Juhász, Kummer ed. 1997). The combustible part of the free gas with condensate is 84.2%, the calorific value is 33 MJ/m^3, CH_4: 75.1%, CO_2: 8.3%, N_2: 7.5%. The C_{5+} content is 35 g/m^3.

Uraiújfalu. The natural gas field situated above the southern part of the Mihályi–Répcelak Variscan basement high range was found by the M–12 well in 1963 (Kőrössy 1987). Ten reservoirs (I/A–III/F) are situated in the Upper Pannonian sandstone, in the traps formed by tectonic closure or lithofacies changes (Völgyi et al. 1985). The depth of GWCs is 1,020–810 m bsl., the calorific value of the combustible gas is 14.2–26 MJ/m^3, the combustible part of the gas 35.2–72.8%, CH_4: 32.3–71.8%, CO_2: 1.1–31.0%, N_2: 26.6-33.8%. The condensate content is 2.9–11.5 g/m^3.

Hydrocarbon exploration areas in Hungary — South Transdanubia – Zala Basin and Dráva Basin



4.2

Ildikó Selmeczi

Exploration history

The area first subjected to exploration in Hungary is situated in the South Transdanubia – Zala Basin and Dráva Basin region. Geological mapping was carried out with the intention to detect hydrocarbon reservoir structures first in the 1916–1919 period and later in the 1930s, in order to demonstrate the continuation of the Sava folds observed earlier in the Muraköz through measurements of the dip conditions of the surface and near-surface formations (Kovácsvölgyi et al. 2003a).

Hydrocarbon exploration in the Zala Basin started in the 1920s, based on the results of field structural geological mapping by Ferenc Pávai-Vajna, and the results of sporadic gravity measurements using the Eötvös torsion balance. The first commercial oil production well in Hungary, Budafa–2, initiated by Simon Papp, began its first substantial petroleum production in November 1937 (Kovácsvölgyi et al. 2003b, Kőrössy 1988). Accompanying this, the first oil pipeline of Hungary was constructed between Budafa (Bázakerettye) and Ortaháza. The well's required filling station was built at the Ortaháza railway station (Dank 1985). Budafa is also known for the experimental seismic measurements carried out there by various foreign companies — among the first in Hungary — from 1935 (Kovácsvölgyi et al 2003b) on.

In the southern part of Transdanubia the Hungarian–American Oil Industry Co (MAORT) carried out gravity and magnetic geophysical measurements using the Eötvös torsion balance in the 1930s, where the Carter Co made seismic, and the Eurogasco carried out gravity measurements. It might be a point of interest from the perspective of the history of explorations that the first well logging was carried out in Hungary at Görgeteg village in the G–1 exploration well in December 1935 (Kőrössy 1989). The well was completed in 1936, and proved dry. Simultaneously, the Inke–I well experienced success, and the moderate sized Inke natural gas field was discovered in May 1936 (Völgyi et al. 1985).

Following the exploration at Görgeteg and Inke, the focus of the drilling exploration shifted from the area along the river Dráva to the Zala Basin area which was explored in parallel and showed spectacular results. There — following the success in the Budafa–Kiscsehi area — oil and natural gas occurrences were found in 1940 in Lovászi and Újfalu. Later on, the Hahót–Pusztaszentlászló oil field (1941), the Hahót–Ederics oil and natural gas field (1945) and the Vétyem, Vétyem East natural gas occurrence (1947) were discovered. The exploration of the Nagylengyel structure started in 1950. The Nagylengyel Nl–1 well, placed on the measured gravity maximum in 1951, failed, but the Nl–2 well drilled in the same year found an oil field. It was the most important oil field of the country to that date. In order to explore the surroundings of Nagylengyel, a number of wells were drilled from the 1950s. Further occurrences became known in the 1960s and 1970s (Kilimán 1952, Barabásszeg 1958, Zalatárnok 1962, Budafa Deep carbon dioxide gas occurrence 1966, Szilvágy 1968, Szilvágy South and Ortaháza 1970, Pusztamagyaród 1972, Pusztaapáti 1973, Budafa–Oltárc 1975) (Völgyi et al. 1985, Kőrössy 1988). In the second part of the 1970s the Nagybakónak and the Sávoly oil and natural gas fields were discovered (Völgyi et al. 1985, Strázsi 1995, Juhász, Kummer ed. 1997). In the 1980s further drilling exploration started in the Nagybakónak area, and in the 1990s successful explorations took place in the Sávoly and Zalakomár regions (Nab-É–1 and Nab–I wells, Sávoly South-east and Sávoly South oil fields, as well as the Sávoly East CO_2 rich mixed gas accumulation, and the Zalakomár oil occurrence) (Juhász, Kummer ed. 1997, Molnár et al. 1999a, Hatalyák et al. 2004). In the 90s 3D seismic measurements were also carried out in certain areas of the region, and from 1995 on the use of modern digital seismic interpretation software has allowed more accurate identification of the horizons and structures within the various successions.

Geological–geophysical exploration of the Middle Miocene deep basin in the Őrség area started only in the 1950s. The first successful drilling was the Csesztreg Cse–I, discovering commercial mixed gas accumulation in 1978. Exploration of the Bajánsenye–Őriszentpéter area was unsuccessful up to the mid-1980s; at that time the Bajánsenye Baján–1 well (1986) discovered a natural gas field (Völgyi et al. 1985, Kőrössy 1988, Bernáthné et al. 1997a, Tormássyné et al. 1992).

In the 1990s the Mol Hungarian Oil and Gas Plc carried out geophysical measurements in the Zala Basin and the wider surroundings. Explorations were followed in the 90s in the Ortaháza – Hahót South, Nagylengyel South, the Sávoly and the Kálócfa, and later on in the Zalabaksa, Szentpéterfölde, Vétyem, Bocska, Milejszeg and Zalakomár areas (Molnár et al. 1998a, b, 1999a, 1999b; Jósvai et al. 2001a, b; Kovácsvölgyi et al. 2003a, b; Laukó et al. 2004; Hatalyák et al. 2004). Mol Plc carried out hydrocarbon exploration from 2004 to 2012 in Gellénháza, from 2001 to 2011 in Kerkabarabás, and from 2001 and 2013 in the Mikekarácsonyfa area (Németh et al. 2012, 2013a; Szabó-Horti et al. 2012). The purpose was to clarify the morphology and structure of the basement, and to detect the structural and stratigraphic traps formed in the Late Miocene Pannonian formations.

Primarily the interpretation of 2D and 3D seismic data and sequence stratigraphic analysis were used. From among the wells drilled during the most recent prospecting efforts of Mol Plc oil traces were found in the Kerkabarabás Kerb–1 well, and in the wells located on the basis of gravity and seismic measurements at the eastern–north-eastern edge of the Gellénháza trough, but no commercial oil-occurrence was found. On the other hand, substantial natural gas resources were found in the Bak–Nova trough by the Gutorfölde–1 and Rádiháza–1 wells, which were extended into the stratigraphic traps of the Lower Pannonian formations.

The Rába Xpronet Company explored the Middle Miocene structural traps in the Nagylengyel area at the end of the 1990s. Two wells were drilled, but only traces of gas could be detected (Körmend.ME–1, Csákánydoroszló Csdor–1 wells) (XPRONET 2001).

In the course of recent geological research carried out by Blue Star '95 Ltd the natural gas reservoirs discovered in the neighbouring Somogysámson in 1984 could be identified in Horvátkút as well (GYARMATI 2008).

Magyar Horizont Energia Kft (Hungarian Horizon Energy Ltd) obtained concession rights in the Őrség in 2005 and drilled the HHE.Őriszentpéter.ÉK–1 hydrocarbon exploration well in 2009, which proved dry. The company gave up its exploration licence for the area in 2013 (no final report was made).

Explorations in the southern part of Transdanubia and in the Dráva valley were re-started only in the 1950s, and delivered results in a series: April 1954, the Buzsák oil occurrence; August, the Görgeteg–Babócsa natural gas and oil occurrence; in 1955, the Bajcsa natural gas field; in 1957, the Heresznye oil and natural gas field. The Babócsa and Heresznye drilling exploration was continued towards the east and in 1958 a small local oil accumulation was found in Szulok. The oil and natural gas field of Vízvár was found in 1959, and later with the extension of the Görgeteg–Babócsa exploration the Görgeteg–Babócsa-East natural gas field was discovered in 1960. In 1961 the hydrocarbon explorations in South Transdanubia were continued in the light of the explorations made so far in the Tarany, Pat, Semjénháza, Somogyudvarhely areas, and in 1962 in the Lábod, Rinyaszentkirály, Szenta areas. In 1963 the Belezna oil and natural gas field became known, and exploration of the anticipated hydrocarbons in the Iharosberény, Nagykorpád, Nagyrécse, Okorág, Vése, Zákány areas was started. Jákó, Kutas, Nagyatád, Berzence, Bolhás, Kisdobsza, Nagybajom, Kadarkút, Komlósd and Sellye were explored in the 1964–66 period. The Mezőcsokonya natural gas occurrence became known at this time as well (VÖLGYI et al. 1985, KŐRÖSSY 1989, MOLNÁR 1998c). In the 1970s, attention was again turned to the southern and south-western parts of Transdanubia after a pause of several years. Exploration was started at Felsőszentmárton and Gyékényes, and later in the Cún and Somogyhatvan areas. An oil and natural gas occurrence was found in Darány in 1975, and in the Liszó natural gas field. In Pátró, carbon dioxide gas was found in 1976. More exact geological mapping was made possible by seismic exploration methods which used modern digital instruments, starting from the mid-1970s. This also contributed to the 1979 discoveries by the OKGT (Hungarian National Oil and Gas Trust) of the Barcs West natural gas field in the basin basement rocks, and the Homokszentgyörgy oil and natural gas field. (KÓKAI et al. 1987).

In the early 1980s the exploration of Rinyaújlak, Somogysámson and Hetvehely yielded few results. Hydrocarbon exploration took place in the Dráva Basin area in 1980–81 under Hungarian–Yugoslavian cooperation. The Vízvár North gas and gas condensate occurrence became known as a result of the Víz–I well drilled in 1979–1980. The OKGT (Hungarian National Oil and Gas Trust) also drilled the Kkut–2 well in Kadarkút, and found oil (KŐRÖSSY 1989, MOLNÁR et al.1997). After the unfruitful attempts of the 1960s, oil and mixed gas reservoirs were found in 1989 in the Pat area, in the Pat–5 and –7 wells. These were drilled where small, separated indications were explored by high resolution seismic measurements. The Iharos natural gas and the Jankapuszta oil occurrences became known in the first half of the 1990s (JUHÁSZ, KUMMER ed. 1997), the Csombárd natural gas field (Csom–1 well, 1997) at the end of the 1990s (MOLNÁR et al. 1998c). From the 1990s, advances in geophysical research methods meant that high resolution 3D surveying could detect traps of small areal extent (unknown earlier). Sequence-stratigraphic testing of the Pannonian formations was also highlighted.

The Magyar Horizont Energia Kft. (HHE Ltd) carried out exploration in the surroundings of Barcs from 1999 on, and in the Mecsek (Ibolya) prospecting area as well. Seven wells were drilled in the Barcs block during the exploration finished in 2011, on the basis of the existing data, renewed processing of the available information and results of the new 3D seismic measurements. The HHE–Istvándi–1, –2, –4 and the HHE–Jánosmajor–2 wells discovered oil and natural gas reservoirs in Lower Pannonian formations, in the Middle Miocene Badenian carbonate rocks and in the Palaeozoic basement successions. The Mecsek (Ibolya) mining plot activities were restricted from 2012 on to the "Szigetvár", "Harkány", "Mohács" and "Gara" blocks (MHE 2011, JÁRAI et al. 2013, CSIZMEG et al. 2014). In 2001 the Törökkoppány Tk–1 well drilled by Winstar Magyarország Kft. (Winstar Hungary Ltd) discovered a commercial natural biogene gas accumulation (El Paso Magyarország Ltd, 2002).

Mol Hungarian Oil and Gas Plc discovered commercial condensate gas reservoir in the Vízvár North exploration area in the second half of the 1990s (GELLÉRT et al. 2006). There was no new discovery in the Péterhida area, but a number of state-of-the-art tests were completed. Besides the 3D seismic measurements and the exploration wells, direct hydrocarbon exploration measurements were used, such as radon content measurement of soils and micromagnetic and electromagnetic frequency measurement. In addition, the geological data of the transboundary area received from INA Naftaplin were processed (HORVÁTH et al. 2011).

Mol Plc followed the exploration work in the Mecsek West area in the period between 2000 and 2012 in order to recognise the structural elements in the zone near the national border, which had been poorly explored earlier (GELLÉRT et al. 2012). As a result of the cooperative exploration work of Mol and the Croatian INA, commercial quantities of combustible natural gas and some condensate were discovered in the Middle Miocene Badenian sandstone and carbonate breccia–conglomerate succession by the well Zaláta–1 (2007). The Croatian part of the gas accumulation was explored by the Dravica–1 well drilled in 2008 (GELLÉRT et al. 2012).

Geological overview

The basement of the area (Figure 4.2.1) consists of formations belonging to the various structural units of the three mega-units of the Alps–Carpathians–Dinarides region, i.e., the Alcapa, the Mid-Hungarian Mega-unit and the Tisza Mega-unit (HAAS et al. 2010). The basement of the north-western and western edge of the area is composed of the metamorphic

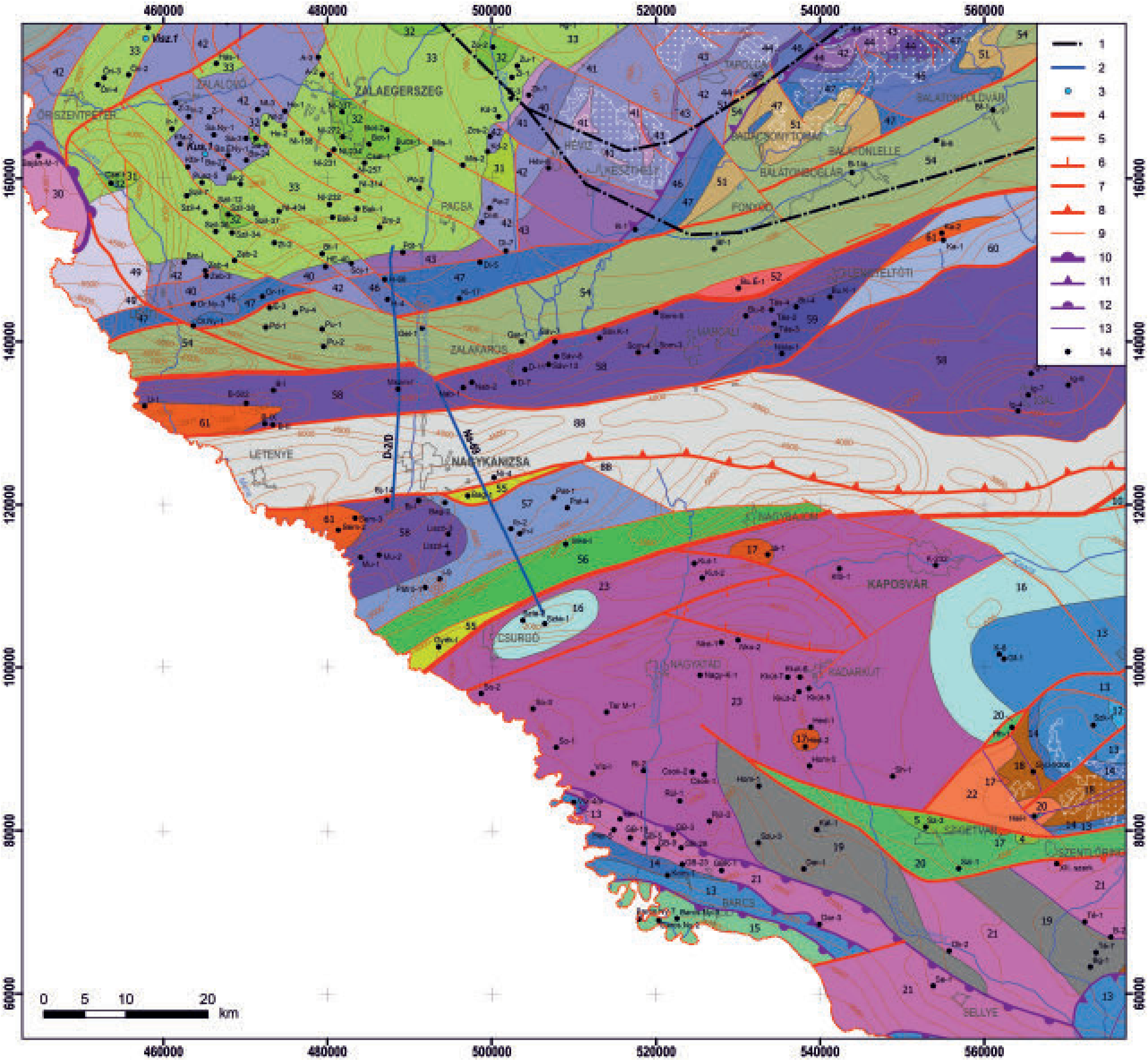


Figure 4.2.1. Pre-Cenozoic geological map of the South Transdanubia - Zala–Dráva area (HAAS et al. 2010)

Legend: 1. boundary of the sub-basin, 2. trace line of the sample 2D seismic sections in this chapter, 3. location of wells including sample geophysical logs of figures in this chapter, 4. first-order Cenozoic displacement, 5. second-order Cenozoic tectonic component, 6.second-order Cenozoic normal fault, 7. second-order Cenozoic displacement, 8. second-order Cenozoic reverse fault, 9. third-order Cenozoic tectonic component, 10. first-order Mesozoic nappe boundary, 11. second-order Mesozoic reverse fault, 12. second-order Mesozoic nappe, 13. third-order Mesozoic tectonic component, 14. wells hit the pre-Cenozoic basement

Legend for geological formations: 4. Albian basinal marls and clastic slope deposits, 5. Lower Cretaceous platform limestone, 10. Lower and Middle Jurassic pelagic, fine-grained siliciclastic beds, 12. Upper Triassic to Lower Jurassic coal-bearing siliciclastic beds, 13. Middle Triassic shallow-marine siliciclastic and carbonate beds, 14. LowerTriassic siliciclastic formations of fluvial and delta facies, 15. low-grade metamorphic Mesozoic formations, 16. Mesozoic formations in general, 17. Permian rhyolite, 18. Permian continental siliciclastic beds, 19. Upper Carboniferous continental siliciclastic complex, 20. Early Palaeozoic low-grade metamorphic complex, 21. Variscan medium-grade metamorphic formations (gneiss, mica, marble), 22. Variscan granitoid rocks, 23. Variscan metamorphites (gneiss, mica, amphibolite), 28. Variscan, low-grade metamorphic Lower Palaeozoic formations (phyllite, metasandstone). 30. Variscan metamorphic formations with Alpine overprint (phyllonite, milonite), 31. Senonian continental siliciclastic and paludal formations, 32. Senonian platform limestone, 33. Senonian basinal limestone and marl, 40. Upper Triassic – Lower Jurassic platform limestone, 41. Norian–Rhaetian and lowermost Jurassic basinal cherty limestone, dolomite, 42. Carnian–Norian platform dolomite, 43. Carnian basinal marl and limestone, 44. Anisian–Ladinian basinal limestone, cherty limestone with tuff intercalations, 45. Ladinian–Carnian platform dolomite, 46. Anisian shallow-marine limestone and dolomite, 47. Lower Triassic shallow-marine fine siliciclastic and carbonate beds, 49. Upper Palaeozoic and Mesozoic formations in general, 51. Middle and Upper Permian continental siliciclastic beds, 52. Upper Carboniferous – Lower Permian granitoid plutons, 54. Variscan low-grade metamorphic,Early Palaeozoic formations (phyllite, limestone, metavolcanic rocks), 55. Senonian pelagic marl, 56. Jurassic–Cretaceous melange, 57. very low-grade metamorphic Triassic–Jurassic formations of slope and basin facies, 58. Middle–Upper Triassic carbonate formations of platform and basin facies, 59. Lower Triassic shallow-marine claystone, marl, limestone, 60. Upper Palaeozoic and Mesozoic formations in general, 61. Permian shallow-marine siliciclastic and carbonate beds, 88. inadequately evaluable or unknown basement

rocks of the Penninic Unit belonging to the Alcapa, and of the Upper Austroalpine Unit (HAAS, BUDAI ed. 2014). The rocks of the Transdanubian Range Unit can be found in much of the basement in the Zala area. This unit is the uppermost non-metamorphic member of the Austroalpine nappe system (HORVÁTH 1993, TARI, HORVÁTH 2010).

The South Zala and North Somogy parts of the area, i.e., the strip south of the Lake Balaton in parallel with the lake, is situated in the territory of the Mid-Hungarian Mega-unit and within it the Mid-Transdanubian Unit. This structural unit is positioned between the Mid-Hungarian structural zone and the Balaton Line, and consists of nappe units comprising pre-Neogene formations (CSÁSZÁR 2012). Rocks of the pre-Cenozoic basement are known from boreholes only.

The pre-Cenozoic basement of the southern part belongs to the Tisza Mega-unit, which basically comprises a series of nappes and consists of three major nappe units. Two of them — the Mecsek Unit to the north and the Villány–Bihor Unit to the south of it — are part of the build-up of the basement in the area.

Basement complex

Alcapa Mega-unit

The low-grade metamorphic Jurassic – Lower Cretaceous rocks of the Penninic Unit can be studied on the surface in the surrounding of the Kőszeg Mountains, and the Upper Austroalpine Unit occurs in the basement to the east and south of the Penninic Unit. The Szentgotthárd wellbores and the Bajánsenye Baján M–1 well explored the low- and medium-grade metamorphic formations here (HAAS, BUDAI ed. 2014), which contact tectonically with the Mesozoic rocks of the Transdanubian Range Unit (FODOR et al. 2003, HAAS et al. 2010).

The oldest known formations of the Palaeozoic basement of the Transdanubian Range Unit include the Ordovician–Devonian slaty aleurolite and shale intercalated with siliceous shale and sandstone intercalations, and the Ordovician–Silurian epimetamorphic quartzphyllite (Figure 4.2.1). In the Gelse area Upper Carboniferous granite is also known (MOLNÁR et al. 1999a). The typical Upper Permian formation of the mountain range, i.e., the Balatonfelvidék Sandstone Formation was explored in Dióskál (KŐRÖSSY 1988).

The Mesozoic sequence of the Transdanubian Range Unit in the Zala Basin occurs in great depths and is covered with Cenozoic sediments. It is predominantly made up of the Triassic and Upper Cretaceous formations. Jurassic – Lower Cretaceous formations of various facies are preserved only in small erosion patches in the basement of the Zala Basin.

Lower Triassic argillaceous marl and sandstone (Hidegkút Formation, Or-Ny–1), as well as compressed calcareous clay and anhydritic marl (Csopak Marl Formation, Or–11) were located in the Ortaháza area (KOVÁCSVÖLGYI et al. 2003a, JÓSVAI et al. 2001b, MOLNÁR et al. 1998a). The brecciated dolomite with limestone intercalations on the top, representing the lower section of the Middle Triassic (Aszófő Dolomite Formation) is also known from the Ortaháza wellbores. The middle and upper section of the Middle Triassic is composed predominantly of deep-sea limestone, marl, tuffite and cherty sediments (Felsőörs Formation, Buchenstein Formation) (Ortaháza, Kehida, Bajcsa, Pusztaapáti). The lower section of the Upper Triassic is made up of marl and calcareous marl deposited in the intraplatform basin (Veszprém Marl Formation in the vicinity of Nagylengyel, Ortaháza, Hévíz, Dióskál, Pötréte, Kehida and Nagytilaj) (KŐRÖSSY 1988). Platform limestone and dolomitic limestone (Ederics Limestone Formation) are also known from Dióskál (MOLNÁR et al. 1998b). The upper section of the Upper Triassic is represented by shallow-marine platform carbonates (Main Dolomite Formation) of large areal extent and great thicknesses. Norian–Rhaetian intraplatform basinal formations are also widespread; their lower section comprises bituminous and laminated dolomite (Rezi Dolomite), and the upper section is made up of marl and argillaceous marl (Kössen Formation). Formation of the Senonian basins started in the Santonian Age of the Late Cretaceous, and in the Zala Basin those sediments are important for hydrocarbon exploration. The formations of the Upper Cretaceous sedimentary cycle unconformably overlie the surface of the pre-Senonian rocks, which underwent folding, uplifting and erosion during the Austrian phase (HAAS et al. 1984). The marl of mid- and deep-sublittoral facies (Jákó Marl Formation) is frequently underlain by basal breccia and conglomerate. The shallow-marine rudist limestone (Ugod Limestone Formation) was developed from the Jákó Marl with continuous transition, and is overlain by the basinal marl (Polány Marl Formation). The Ugod Limestone was deposited directly on the pre-Senonian basement in the elevated areas of the Late Cretaceous basin. The Upper Cretaceous succession in the sub-basin is a couple of hundred metres thick.

Mid-Hungarian Mega-Unit

Formations of the Mid-Transdanubian (Sava) Unit constitute part of the Mid-Hungarian Mega-unit. The oldest one is the foliated siltstone categorised conditionally as Carboniferous (Tornyiszentmiklós Clay Shale Formation, U–I well). It is conformably overlain by the Lower Permian anchimetamorphic shale (Trogkofel Formation). There, in the Upper Permian caprock, foliated claystone, laminated sandstone, siltstone beds can be found (Gröden Sandstone Formation); based on the U–I borehole its thickness can be assumed to be 200–300 metres (GYALOG, BUDAI ed. 2004). The Permian beds are closed by a dolomitic limestone–dolomite–claystone–dolomitic limestone breccia sequence (Tab Dolomite Formation), with an estimated thickness of 100–150 metres.

In the Triassic sequence of the Mid-Transdanubian Unit, the Lower Triassic is represented by: limestone; marly-sandy limestone; sandstone; sandy, gastropod-bearing oolitic limestone. It comprises echinoderm fragments and brecciated dolomite (Buzsák Formation), The Middle Triassic (Anisian) is made up of limestone and authigenic breccia-bearing limestone of carbonate ramp facies in a thickness exceeding 200 metres, with frequent dolomite intercalations (Táska Formation). The Ladinian Murakeresztúr Sandstone Formation is known from the Budafa B–502 and the Nagybakónak Nab–2 wells, consisting of more than 70% sandstone with rhyolite clasts, radiolarian claystone and limestone intercalations. The Middle Triassic (Ladinian) and the Lower Carnian is predominantly made up of the authigenic breccia-bearing Som Formation and the pelagic Sávoly Limestone Formation consisting of tuffaceous limestone, with laminitic marl intercalations. The marl and sandy limestone layers intercalating the carbonate sequence of platform facies are listed as the Újudvar Marl Formation (Rálischné Felgenhauer 2004). The uppermost part of the Carnian–Norian Stage is represented by shallow-marine platform carbonates analogous with the Dachstein Limestone and the related sediments of slope facies (Igal Formation) (Bércziné Makk 1988, Budai, Konrád 2011).

Tisza Mega-unit

The pre-Alpine basement is made up of complexes which have undergone various grades of metamorphosis. These form the pre-Cenozoic basement in the area between Kaposvár, Csurgó and Sellye, and to the south of Szentlőrinc. In the western and southern forelands of the Mecsek, the basement ascends to 500 metres below sea level. The basement consists of the Baksa Complex of composite structure in the “Görcsöny ridge” between the Mecsek and the Villány Mountains, made up of alternating low-, medium-, and high-grade gneiss–mica with amphibolite, marble, dolomarble intercalations (Szederkényi 1996a). In the basement of the Dráva Basin, between Csurgó and Sellye the Babócsa Complex of north-west–south-east strike can be found. This basically consists of the alternation of strongly folded gneiss and two-mica schist (Szederkényi 1996b). The crystalline basement crops up at the surface across the national border. The Ófalu Phyllite Formation, which can be considered as a chaotically folded megabreccia (melange) which underwent low-grade metamorphism, is found in a strip in the southern foreland of the Mecsek. The original rock of the metamorphites was also formed in the Early Palaeozoic. The Upper Carboniferous Téseny Sandstone Formation of fluvial–delta–lacustrine facies unconformably overlies the crystalline basement (Budai, Konrád 2011). It is known from Homokszentgyörgy, Kálmáncsa, Darány, Szulok and Téseny wells. It is overlain by the predominantly red coloured Korpád Sandstone Formation; however, in the Dráva Basin, Badenian formations rest on it with a significant unconformity (Budai, Konrád 2011).

The Gyűrűfű Rhyolite Formation — derived from the acidic volcanism associated with the initial continental rifting of the Alpine cycle —, occurs only in small patches (for instance Hed–2 wellbore, where it overlies the Mórágy Granite, and is unconformably overlain by the Miocene “Lajta Limestone”). The products of the denudation after the Variscan orogenesis include the fluvial and lacustrine formations ranging from the Permian to the Lower Triassic, representing a thick cyclic continental sedimentary sequence (Cserdi Conglomerate, Boda Aleurolite and Kővágószőlős Sandstone Formations). A facies similar to the foregoing is represented by the Lower Triassic Jakabhegy Sandstone, exposed in a thickness of 120 metres by the Cún–1 well drilled at the southern national border. Some formations were classified earlier as Devonian, but are currently listed as possibly Mesozoic — these underwent a slight metamorphosis (meta-volcanic rocks, meta-sandstone, dolomitic chlorite schist, dolomite schist, dolomitic anhydrite, crystalline dolomite), and were discovered near Barcs (Kókai et al 1987).

The Middle Triassic predominantly consists of shallow-marine carbonate formations forming an imbricate pattern of the Villány Mountains (Csukma Dolomite Formation), overlying the limestone of deep-water facies (Lapis Limestone and Zuhánya Limestone Formation). Their overlying strata are the Upper Triassic fluvial, delta, and lacustrine sediments (Mészhegy Sandstone Formation). At the Cún–1 well, the older Middle Triassic dolomite (Hetvehely Formation), characterised by dark grey gypsum and anhydrite intercalations, tectonically overlies the Jakabhegyi Sandstone.

The Jurassic pelagic limestone succession of the Villány Mountains — dissected by hiatuses —, are separated by unconformity both towards the underlying Upper Triassic, and towards the overlying Lower Cretaceous (Nagyharsány Limestone Formation) beds. It is worth mentioning that the Jurassic formations of the Mecsek Unit include the Lower–Middle Jurassic pelagic marls (Vasas Marl, Komló Calcareous Marl, Dorogó Calcareous Marl, Óbánya Siltstone Formations), which can be taken into account as potential source rocks, even though no hydrocarbon accumulation was found there so far. The extension of the Cretaceous formations in the area of the Mecsek Unit is insignificant: Upper Jurassic – Lower Cretaceous cherty limestone of bathyal facies (Márévár Limestone Formation) at Kurd and the Mecsekjánosi Basalt were located. In the Dalmand–1 well drilled in 2001, there is at the maximum depth conglomerate, sandstone, marl, tuff, tuffaceous sandstone and cherty marl belonging conditionally to the Cretaceous or the Eocene (Kovács Zs. ed. 2013).

Basin fill formations

Palaeogene: Eocene formations were located in the Bak–Nova trough of ENE–WSW strike, and around Ortaháza in a tectonic fragment. The Eocene sequence is most complete in the Bak–Nova trough; its total thickness in the surrounding of Zalatárnok even after denudation may still exceed 1000 metres (Jósvai et al. 2001b). The Eocene formations unconformably

overlie the Upper Cretaceous or Triassic formations. Due to compression, the Bak–Nova trough was formed somewhat to the south of the Late Cretaceous sedimentary basin axis, where the Upper Cretaceous – Eocene sediments folded up into synclines characterised by steep limbs on both sides. The Eocene sequence is composed of the Middle and Upper Eocene sedimentary formations — such as the sedimentary assemblage containing shallow-marine gravel horizons and carbonaceous intercalations, upwards shifting into biogenic limestone (Darvastó Formation), shallow-marine, biogenic limestone (Szőc Limestone Formation), and marl (Padrag Marl Formation) deposited in the shallow pelagic – bathyal environment and the Bartonian–Priabonian volcanics (Szentmihály Andesite Formation). The volcanics may be hundreds of metres thick; at the Söjtör Zm–3 well, it is nearly 1,000 metres. They can be observed in the Padrag Marl as increasingly thick and numerous intercalations (MOLNÁR et al. 1998b).

The 6–12 km wide "Magmatic–metamorphic zone" of E–W strike is situated south of the Ortaháza–Kilimán high, composed of Triassic carbonates (Figure 4.2.2), along the Balaton Line, which is made up of several rock types (JÓSVAI et al. 2005). The overwhelming majority of the formations consists of tonalite (JÓSVAI et al. 2001b), which can be dated to approximately 30–37 million years ago (Early Oligocene), and is classified conditionally to the Pusztamagyaród Tonalite Complex (Zoltán Balla, verbal communication). As a result of the explorations made by the Mol Hungarian Oil and Gas Plc, new, geographically separated Late Eocene and Oligocene formations were detected in the Sávoly area. The hundreds of metres thick Upper Eocene succession is made up of dark grey, black claystones of fresh-water facies, and is rich in coalified plant remains and sand locally in coal stringers (their lithostratigraphic classification is unclear at present). The Sávoly Oligocene succession, separated geographically from the former, consists of sandy–pelitic sediments dissected by tuff intercalations; this succession shows similarity to the Slovenian Oligocene layers along the Periadriatic Line (JÓSVAI et al. 2005).

In the southern part of the area (Szentlőrinc, Szigetvár) during the Late Eocene a continental succession of cyclic character (clay, silt, carbonaceous clay, brown coal, sandstone, gravel, and conglomerate) were deposited (Szentlőrinc Formation). This several hundred metres thick formation is underlain by the Palaeozoic basement (Pécs XII. structural exploration well, Baksa Complex) or the Nagyharsány Limestone Formation (Szigetvár wellbores), and is overlain by Miocene sediments.

At the beginning of the Neogene, in the Early Miocene, continental sedimentation took place in the area. In the southern and western parts of the region, there were sediments of the Szászvár and the Ligeterdő Formations; in the northwest, the Somlóvásárhely Formation was deposited; locally, intercalations of volcanic origin can be observed in the successions. The most significant succession belongs to the Szászvár Formation, consisting of clastic sediments of different grain size; its thickness at

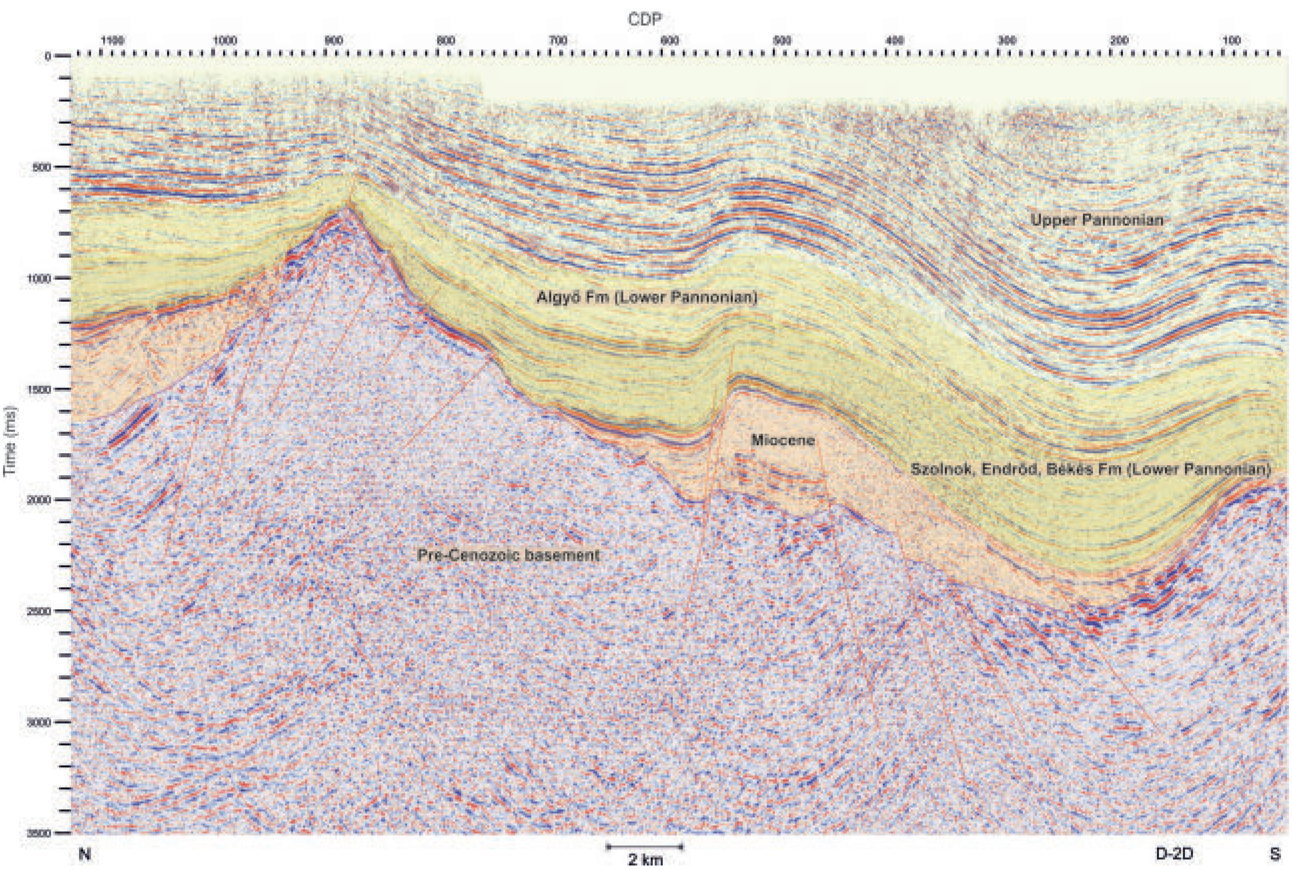


Figure 4.2.2. Seismic profile of N-S direction crossing the western part of the area. On the northern side the highest elevation of the Ortaháza-Kilimán high, the Hahót-Kilimán area and in the southern side the Semjénháza-Bajcsa range of the elevated basement can be observed (for the seismic trace line see Figure 4.2.1)

some places may be as much as several hundred metres (in Inke–I > 500 m). The Ligeterdő Formation of Ottnangian – Early Badenian age may occur in successions of the north-western part (Őrség) of the area. Its material is derived from the rocks of the Alps, brought to the West-Hungarian sedimentary basins by fluvial transport, and may reach a considerable thickness (Lovászi L–II >2,000 m). Occasionally Miocene volcanic bodies (Mátra Volcanic Formation Group) can be found in the formation (Őri–2 well). Its age might be assumed to extend to the Badenian, based on Austrian research data (PASCHER 1991). A widespread formation of considerable thickness in the area is the Budafa Formation of Karpatian–Badenian age. Its sediments of abrasion shoreline, shoreline, delta and lagoonal facies indicating the early period of the transgression were located from a number of wellbores (for instance Zalakaros, Oltárc, Szentliszló, Nagykanizsa–Zákány area, the surrounding of Pat, Marcali, Inke, Sávoly, Somogyzsitfa, etc.). Its maximum thickness in the area exceeds 1,700 metres (Inke–I; Figure 4.2.3). During the early Badenian, thick, fine-grained siliciclastic sediments were deposited in the inner part of the basin (Tekeres Schlier Formation); it comprises tuff stringers. The formations are known from the Őrség–Lovászi–Budafa–Oltárc area, which had marine connections towards the west. In Nagylengyel the glauconitic sandstone bed occurs as an oil reservoir which interbeds in the Badenian grey marl succession, and can be considered as an index layer (KŐRÖSSY 1988).

In the pelagic area the fine-grained siliciclastic sedimentation (Szilágy Clay Marl Formation) was continued in the later period of the Badenian. Due to lack of exact stratigraphic investigations, the Badenian pelitic sequences (Tekeres Formation, Baden Clay Formation and Szilágy Clay Marl Formation) could not be easily defined. The deposition of the some tens of metres-thick Badenian carbonates (Lajta Limestone Formation) was restricted to the former tectonic–palaeo-geomorphological elevations and the shallower margins of the basin areas. At the margin sand around the elevations, hundreds of metres thick, coarse clastic beds of alluvial cone facies (breccia, conglomerate) can be observed locally at the Badenian base (for instance Dráva valley, Barcs-West [MALVIĆ 2006], Zaláta–Dravica field, Zaláta–1 well: 400 m [GELLÉRT et al. 2012]).

Brackish-water sedimentation took place in the area during the Sarmatian. The open-water areas had clay marl, marl, calcareous marl layers of the Kozárd Formation, whereas around the former tectonic–palaeo-geomorphological elevations and along the shallow basin margins the limestone–calcareous sandstone beds of the Tinnye Formation were deposited. The thickness of the pelitic Sarmatian succession at some places may extend hundreds of metres (for instance in the Szentgyörgyvölgy Szen–2 and Kerkafalva Cse–3 wells it exceeds 300 metres). The areal extent of the Tinnye Limestone is sporadic, and its

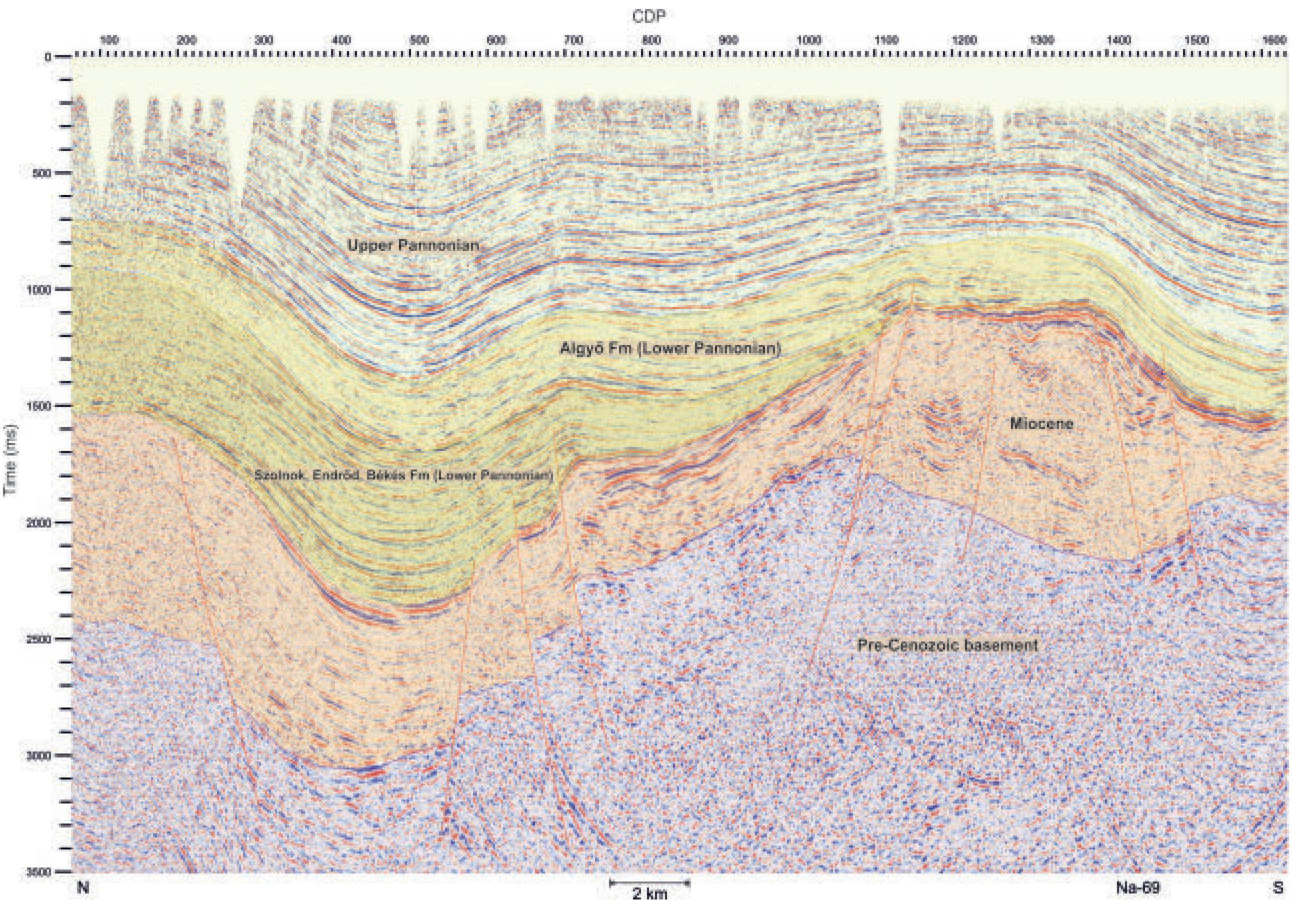


Figure 4.2.3. Seismic section Na-69. It runs approximately in NW-SE direction, somewhat to the east of the one marked D-2D. The Kanizsa deep zone can be seen on the left hand side of the figure, in the north-western part of the profile. The Inke structure is in the south-eastern third of the profile ; the Iharos occurrence can be found here (for the seismic trace line, see Figure 4.2.1)

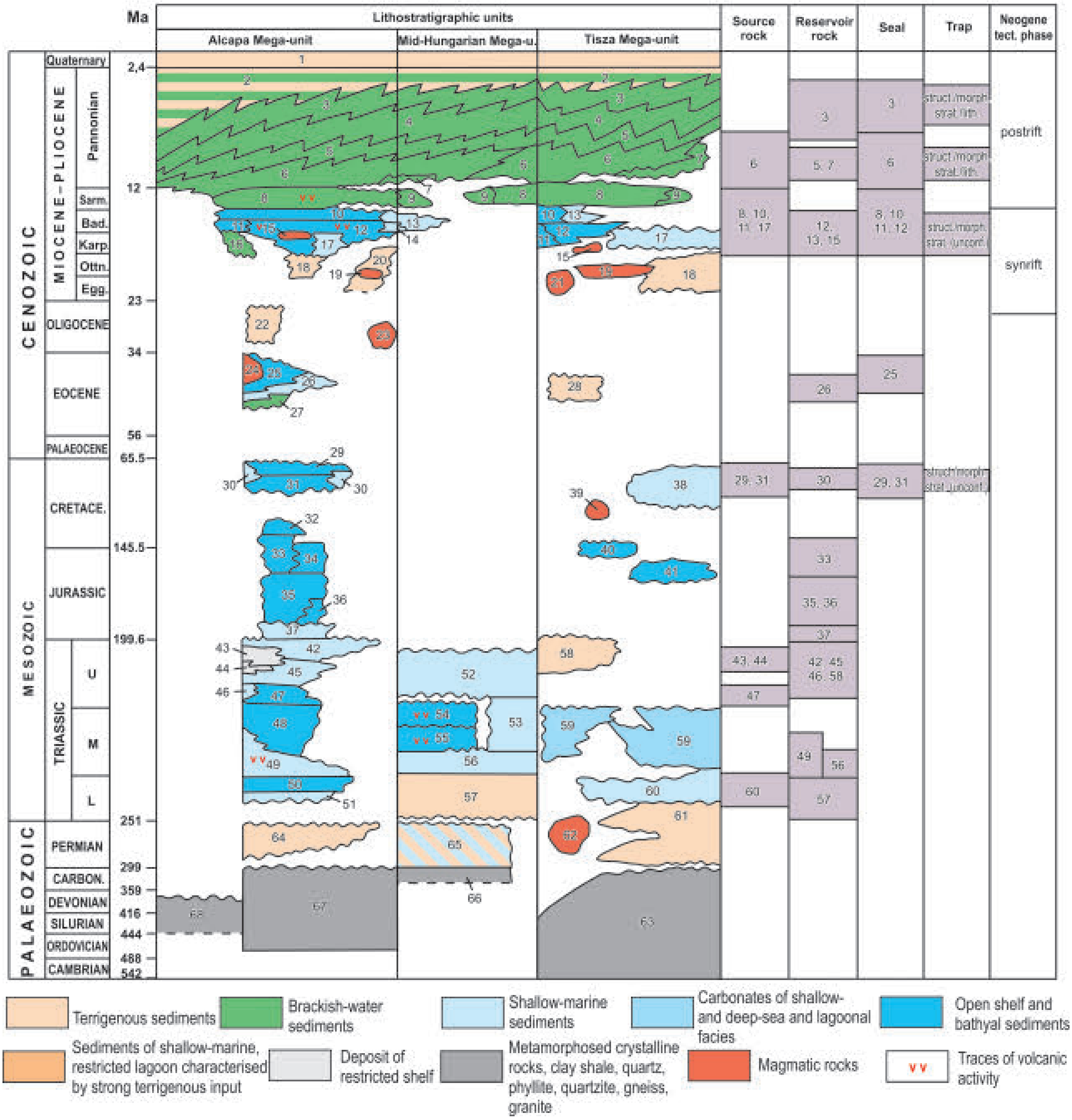


Figure 4.2.4. Litostratigraphic units and the elements of the hydrocarbon systems of the Zala–Dráva Basin area

The beds /formations and their thicknesses: 1. Quaternary sediments (50–700 m); 2. Nagyalföld and Zagyva Formations, consolidated (100–800 m); 3. Újfalu Formation, Somló and Tihany Members, undivided(50–1,400 m); 4. Algyő Formation (100–500 m); 5. Szolnok Formation (100–1,200 m); 6. Endrőd Formation (100–500 m); 7. Békés Conglomerate Formation (0–40 m); 8. Kozárd Formation (0–400 m); 9. Tinnye Formation (0–100 m); 10. Szilágy Clay Marl Formation (0–400 m); 11. Baden Clay Formation (0–300 m); 12. Tekeres Schlier Formation (> 1,000 m); 13. Lajta Limestone Formation (0–100 m); 14. Pusztamiske Formation (0–100 m); 15. Tar Dacite Tuff Formation (0–50 m); 16. Ligeterdő Formation (0–470 m); 17. Budafa Formation (0–600 m); 18. Szászvár Formation (0–300 m); 19. Gyulakeszi Rhyolite Tuff (0–70 m); 20. Somlóvásárhely Formation (0–175 m); 21. Mecsek Andesite Formation (0–600 m); 22. Csatka Formation (0–150 m); 23. Pusztamagyaród Tonalite Complex (0–1,500 m); 24. Szentmihály Andesite Formation (0–1,000 m); 25. Padrag Marl Formation (0–300 m); 26. Szőc Limestone Formation; 27. Darvastó Formation (0–70 m); 28. Szentlőrinc Formation (0–200 m); 29. Polány Marl Formation (0–600 m); 30. Ugod Limestone Formation (0–300 m); 31. Jákó Marl Formation (0–400 m); 32. Sümeg Marl Formation (0–250 m); 33. Mogyorósdomb Limestone Formation (0–100 m); 34. Szentivánhegy Limestone Formation (0–20 m); 35. formations of "ammonitico rosso" facies, undivided (0–10 m); 36. Hierlatz Limestone Formation (0–40 m); 37. Kardosrét Limestone Formation (0–150 m); 38. Nagyharsány Limestone Formation (0–100); 39. Mecsekjánosi Basalt Formation (0–200); 40. Upper Jurassic in general (<100 m); 41. Middle Jurassic in general (0–480 m); 42. Dachstein Limestone Formation (0–160 m); 43. Kössen Marl Formation (0–500 m); 44. Rezi Dolomite Formation (0–100 m); 45. Main Dolomite Formation (0–1,500 m); 46. Ederics Limestone Formation (0–250 m); 47. Veszprém Marl Formation (0–1,000 m); 48. Middle Triassic carbonate formations of basin facies (Felsőörs, Füred and Buchenstein Formations) (0–300 m); 49. Middle Triassic shallow-marine carbonates (Aszófő Dolomite, Megyehegy Dolomite, Iszkahegy Limestone, Tagyon Limestone Formations) (0–800 m); 50. Csopak Marl Formation (0–200 m); 51. Hidegkút Formation (0–100 m); 52. Igal Formation (0–750 m); 53. Som Limestone Formation (0–200 m); 54. Sávoly Limestone Formation (0–500 m); 55. Murakeresztúr Sandstone Formation (?); 56. Táska Limestone Formation (0–200 m); 57. Buzsák Formation (0– hundreds of metres); 58. Karolinavölgy Sandstone Formation (0–50 m); 59. Middle Triassic marine carbonates of shallow and deep or lagoon facies (Hetvehely Dolomite, Rókahegy Dolomite, Lapis Limestone, Zuhánya Limestone Formations), (0–600 m); 60. Patacs Aleurolite Formation (0–60 m); 61. Upper Carboniferous–Permian-Lower Triassic continental formations (Téseny Sandstone, Korpád Sandstone, Cserdi, Kővágószőlős and Jakabhegy Sandstone Formations), (0–1,000 m); 62. Gyűrűfű Rhyolite Formation (0–800 m); 63. Palaeozoic formations older than the Permian: granite, gneiss, mica and other metamorphites (Babócsa Complex and Baksa Complex, > 500 m); 64. Balatonfelvidék Sandstone Formation (0–hundreds of metres); 65. Anchimetamorphic slate, sandstone, carbonates (Trogkofel, Gröden Sandstone and Tab Dolomite Formations) (0–500 m); 66. Tornyiszentmiklós Slate Formation; 67. Lovas Slate, Balatonfőkajár Quartz Phyllite and Velence Granite Formations); 68. Metamorphic crystalline rocks. Trapping: struct./morph.: traps created above a structurally and morphologically formed bottom structure; strat/lith: stratigraphically and lithologically closed traps; unconf: stratigraphic trap formed along the unconformity surface

thickness usually does not exceed 100 metres. In the Dráva valley area the Sarmatian sediments are missing, or their presence cannot be revealed biostratigraphically. It is probably missing in the surroundings of Inke, Iharosberény and Liszó.

The products of volcanic activities taken place in the Miocene can be observed in several parts of the area. The Lower Miocene continental beds are penetrated by the volcanics belonging to the Mátra Volcanic Formation Group around Sávoly; however, the volcanics are known to be very thick around the Mezőcsokonya wells as well (Mcs. West–2: 624.4 m thick, without reaching the underlying formation). Local, intercalations of the Gyulakeszi Rhyolite Tuff Formation can be seen (e.g. Kerkabarabás Kerb–1: 72 m, Kaposfő Kfő–2 well: >700 m); these may form either the underlying (Iharos Ih–2) or the overlying (Inke Pat–4) unit of the continental succession. The tuff intercalations detectable in the Karpatian–Badenian sequences can be associated with the middle rhyolite tuff explosion (Tar Dacite Tuff Formation). The entire pre-Pannonian Miocene is missing at Tolnanémedi above the highly elevated Mesozoic (Kovács Zs. ed. 2013).

At the beginning of the Pannonian the tectonic subsidence was replaced by thermal subsidence (post-rift phase) in the basin areas; occasionally, however, uplifting took place (e.g., in the Kilimán part of the Ortaháza–Kilimán ridge, Figure 4.2.2). With the exception of the more elevated ridges the sedimentation may have been continuous in a significant part of the area at the Sarmatian–Pannonian boundary. In the basinal areas this boundary is drawn in pelitic successions characterised by poor fauna (Endrőd Marl Formation), and is therefore hard to determine. The Endrőd Marl Formation is 100–400 m thick in general. The turbidites of the 100–1,500 m thick Szolnok Formation appear above the marl beds; they contain sand bodies several metres or several tens of metres thick. There the formation reaches its maximum thickness in the Csesztreg and Resznek areas and on the southern limb of the Budafa anticline and in the trough to the south of it. The Szolnok Formation shows tripartition, and the lower and upper parts of the turbidite succession are separated by a thicker pelitic section ("Lenti marl"). The hundreds of metres thick Algyő Formation, deposited above the turbidite, is made up predominantly of silt, which was deposited on the slope which gradually filled up the deeper parts of the Lake Pannon. The slope deposits are overlain by sediments of shallow water facies. In the overlying succession of the Algyő Formation, pelitic beds (reaching a thickness of some hundreds of metres) alternate with upward-coarsening sand bodies (Újfalu Formation). These sand beds were deposited on the delta front and their thickness ranges from some metres to some tens of metres. The sand bodies have a large areal extent laterally (i.e. several tens of kilometres), they are in connection with each other as a rule, and are significant as fluid reservoirs. In the upper part of the succession the sediments of the alluvial plain are overlain exclusively by upward-fining channel sand bodies of low thicknesses. The alluvial plain sediments are classified into the Zagyva Formation; however, lithologically these deposits are similar to those of the delta plains (in the overlying beds), and can be identified only on the upper — some hundred metre-thick section of the Pannonian successions in the deeper basin parts.

In the Quaternary the Pannonian sedimentation was followed first by a significant denudation and later on by the alternation of erosion and periglacial terrestrial–fluvial sedimentation. The thickness of the Quaternary beds may reach hundreds of metres.

The geological formations of the area are shown in Figure 4.2.4, the schematic stratigraphic –sedimentological profile of NW–SE direction, showing the Pannonian formations can be seen in Figure 4.2.5.

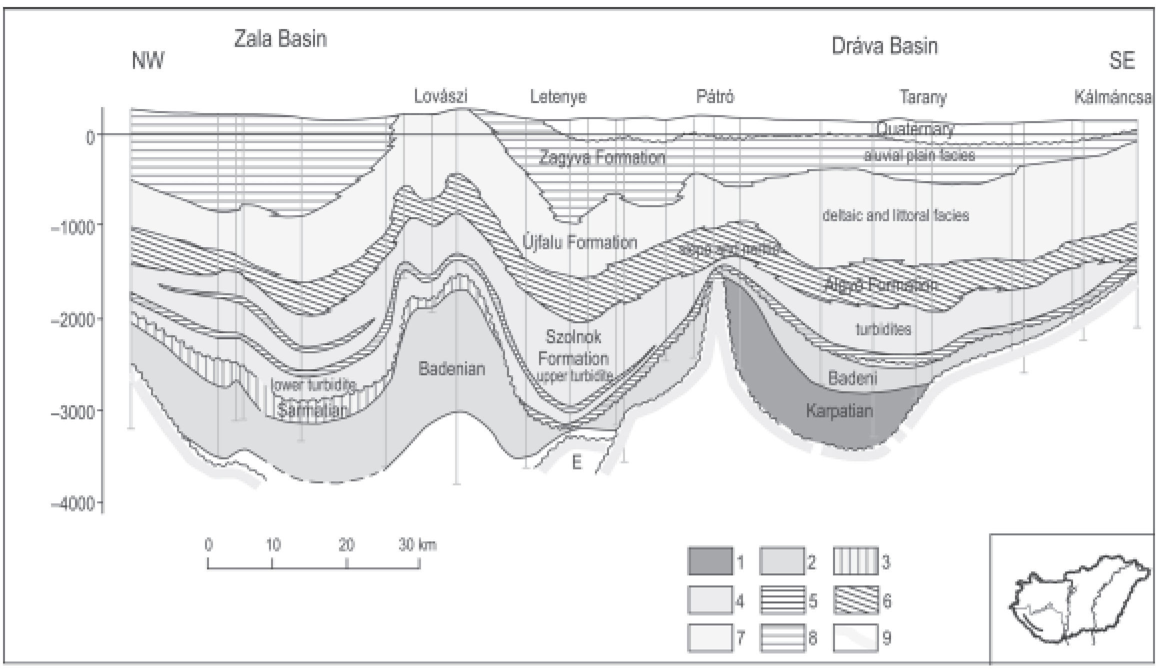


Figure 4.2.5. Schematic stratigraphic–sedimentological profile of NW–SE direction, showing the Pannonian s.l. formations of the Zala Basin and the Dráva Basin (adapted from Juhász 1998)

An overview of hydrocarbon geology

A number of hydrocarbon accumulation zones can be found in the Zala–Somogy–Dráva valley (JUHÁSZ, KUMMER ed. 1997), which are — from the north-east to the south-west — as follows: Szentgyörgyvölgy–Csesztreg natural gas accumulation zone (a.z.); Bajánsenye–Őriszentpéter South natural gas a.z.; Nagylengyel regional oil a.z.; Budafa–Lovászi regional oil and natural gas a.z.; Ortaháza–Hahót regional oil and natural gas a.z.; Semjénháza–Nagyrécse regional hydrocarbon a.z.; Belezna–Mezőcsokonya regional oil and natural gas a.z.; Vízvár–Darány regional oil and natural gas a.z.; (Molve–Kalinovac)–Barcs West regional natural gas a.z.; and Dráva trough eastern part, deep zone. A number of fields and reservoirs are located in these zones. The best quality source rock of the Transdanubian region, the Kössen Formation can be found here. The hydrodynamic flow system of the north-western part of the area especially favours the accumulation of hydrocarbons: the hydraulic pressure exerted by the mountain chains rising to the west and southwest promotes the flow of migrating hydrocarbons towards the Zala Basin (CSIRIK et al. 2000).

The hydrocarbon occurrences of the area can be seen in Figure 4.2.6.

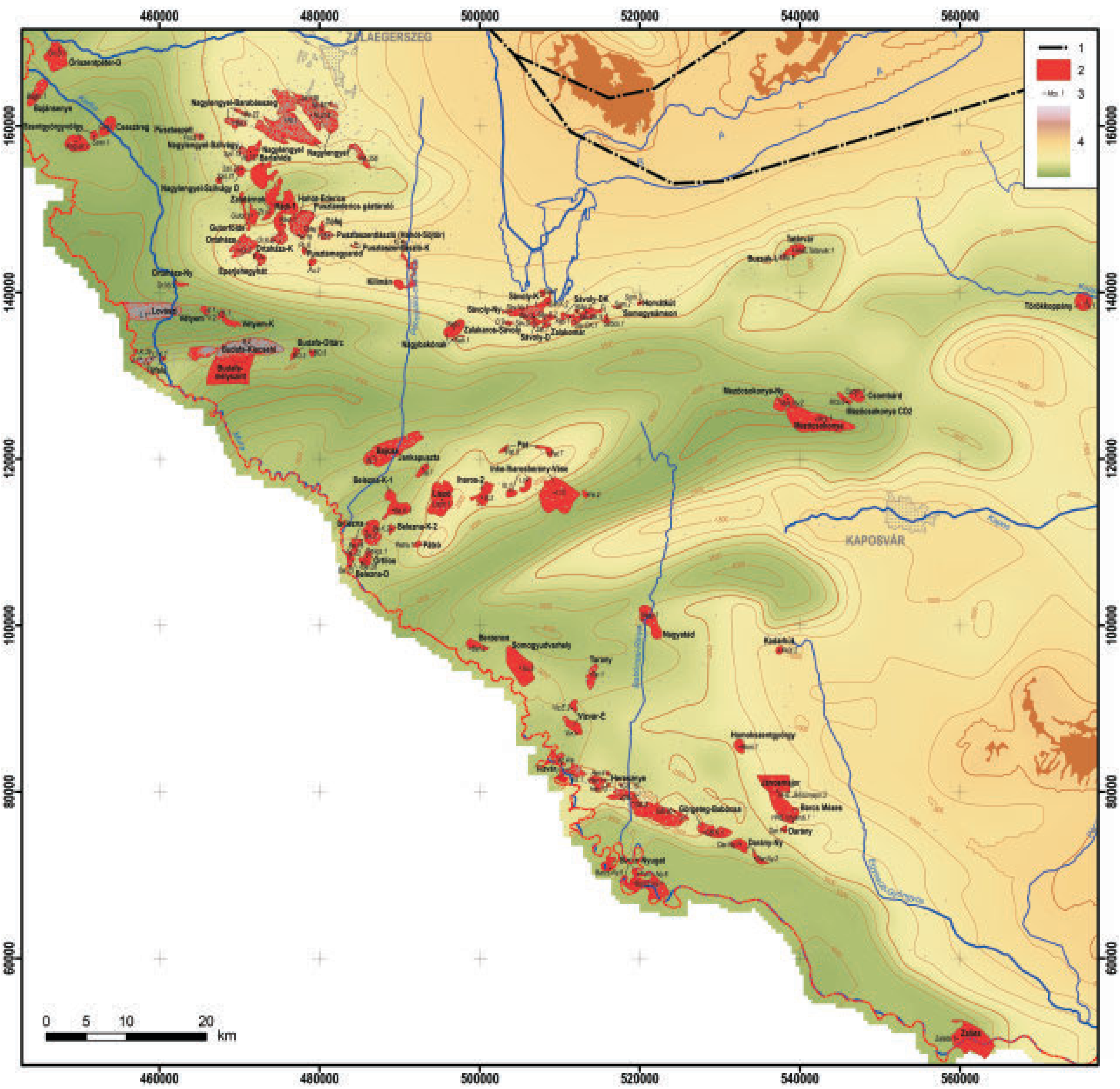


Figure 4.2.6. Hydrocarbon fields of the Zala–Dráva Basin area

1. Boundary of the sub-basins, 2. Conventional hydrocarbon field, 3. Discovery well of the hydrocarbon field, 4. Depth of the pre-Cenozoic basement

Source rocks

Due to the complex geological build-up of the Danube–Dráva sub-basin, hydrocarbons identified in the area might have originated from several source rocks. The Mesozoic source rocks have great significance in the part of the Zala Basin located in the territory of the Transdanubian Range Unit. The oil generating Upper Triassic Kössen Formation can be considered as the best source rock, with an average total organic carbon content (TOC) of 0.82%, and an oil productivity index (OPI) of 0.25 (NÉMETH et al. 2012, LAUKÓ et al. 2004). It is encountered mainly to the north-east of the Nagylengyel oil field, and in the Bak–Nova trough. The thickness of the Kössen Formation in the Zala Basin approaches 600 metres, with an average thickness of 200 m, and an areal extension of approximately 1500 km^2 (BADICS, VETŐ 2012). The vitrinite reflectance value is above 0.6%, representing the oil window. Due to its kerogen type (IIS), oil can be generated by a lesser extent of burial (temperature), as in the case of the Neogene source rocks. The Kössen Formation was only able to enforce its oil generating potential when buried at an appropriate depth during the Neogene (MOLNÁR et al. 1998b). In terms of hydrocarbon generation, the Kössen Formation is followed by the Upper Cretaceous Jákó Marl Formation, which is also characterised by a high hydrocarbon potential. It has a 0.7% TOC and 0.32 OPI value, and based on the vitrinite reflectance values exceeding 0.6%, it is in the oil generating zone. Its kerogen is mainly oil generating, and in a subordinated manner gas-generating (LAUKÓ et al. 2004). Among the Upper Triassic formations, the Norian Rezi Dolomite and the Carnian Veszprém Marl have significant organic matter content and hence may also be deemed hydrocarbon generating. The latter is characterised by 0.43% TOC and 0.22 OPI. It would generate primarily wet and dry gas. The oil generating potential of the Veszprém Marl is less than that of the Kössen and Jákó Formations, in part because of the high level of thermal maturity of the formation (LAUKÓ et al. 2004). The marly developments of the Main Dolomite Formation are characterised by lower hydrocarbon potential (SZABÓ-HORTI et al. 2012). The Upper Cretaceous Polány Marl Formation is relatively poor in organic matter, and has only gas generating potential (LAUKÓ et al. 2004). The intrusion of the tonalites and the andesites in the couple of kilometres wide "Magmatic–metamorphic zone" along the Periadriatic–Balaton Line system promoted the maturation of Kössen Formation and Veszprém Marl Formation found in great quantities in the Bak–Nova trough (KOVÁCSVÖLGYI et al. 2003a). (The "Magmatic–metamorphic zone" is dry in terms of both hydrocarbon generation and storage; the rocks have low Corg contents [JÓSVAI et al. 2001b, 2005, KOVÁCSVÖLGYI et al. 2003a]).

Among the basin filling formations, the potential source rocks are the pelitic Middle Miocene, and Upper Miocene Lower Pannonian sediments. They are widespread in the Zala Basin primarily in the Resznek deep zone in the Lovászi depression, in the Budafa trough and in the Kanizsa deep zone. Their organic matter content and their kerogen are both favourable, as their maturity took place at the end of the Neogene and during the Quaternary. The vitrinite reflectance values of the Badenian pelitic rocks vary in a range of 0.8–1.2%. They are found in the main zone of oil generation in the 1,870 and 3,450 metres range possessing Type II kerogen, while the Lower Pannonian fine-grained siliciclastic sediments contain Type III or II–III kerogen (MOLNÁR et al. 1998a, KOVÁCSVÖLGYI et al. 2003a).

As a result of examinations of genetic nature, three oil types were distinguished in the area located north of the Bak–Nova trough (KONCZ 1990), which originated from at least three types of source rock. The high sulphur containing heavy oils (Nagylengyel, Barabásszeg, Szilvágy, Pusztaapáti) originated from the Upper Triassic Kössen Marl and from the Main Dolomite. The intermediate–naphthenic type oils and gas condensates were predominantly generated by Middle Miocene source rocks. The source rock of the naphthenic type light oils and gas condensates should be sought among the Upper Cretaceous and Badenian formations (JÓSVAI et al. 2001a, LAUKÓ et al. 2004). The overwhelming majority of the oils in the vicinity of Sávoly had low level of thermal maturity. The correlation tests of oil and source rock suggest that oils accumulated in the Mesozoic carbonate beds originated from Badenian source rocks. The overlying Pannonian marls and calcareous marls contain more gas generating kerogen (HATALYÁK et al. 2004).

The subsidence history of the Zala Basin in the area around Nagylengyel is shown in Figure 4.2.7.

The hydrocarbon accumulations in

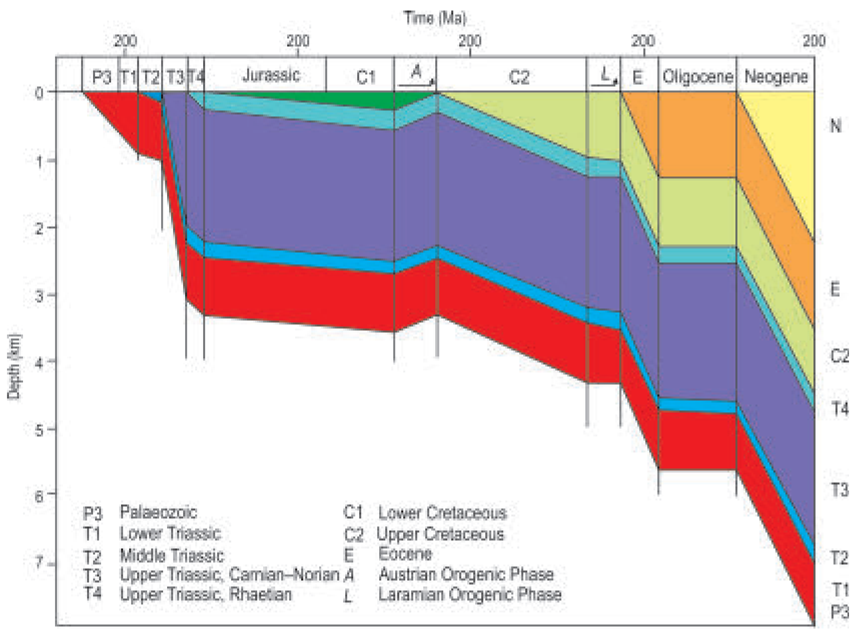


Figure 4.2.7. Burial history of the Zala Basin in the surroundings of the Nagylengyel oil field (after CLAYTON, KONCZ 1994b)

the Dráva Basin area are mostly derived from the thick Neogene sediments rich in organic matter contents, and can be found in the deeper parts of the basin (GELLÉRT et al. 2006, 2012; HORVÁTH et al. 2000). The pre-Pannonian Miocene argillaceous marls, marls (Tekeres Schlier, Szilágy Clay Marl Formation, Kozárd Formation) and calcareous marls (Lajta Limestone Formation) situated in the deep trough with the favourable 0.5–1.5 TOC content can be rather considered as source rocks which might easily have got into the oil and even the gas generation window. Due to their small extension and negligible thickness the role of the Sarmatian pelitic rocks is subordinated. Pannonian basal marls (Endrőd Formation Belezna Calcareous Marl Member, Nagylengyel Clay Marl Member, and Szolnok Sandstone Formation Lenti Marl Member) can also be seen as source rocks. They can only be considered source rocks in the deep zone areas, as in the lesser depths they have not yet got to the oil generation zone (GYARMATI 2008, HHE 2011, NÉMETH et al. 2013b). In the deepest part of the Neogene depression, deeper than 4,000 m in the Croatian part of the basin, the Miocene and the Lower Pannonian pelitic successions are of substantial thickness and large extension (HANGYÁL, DANK 1975).

Based on geochemical analysis results carried out in the surroundings of Péterhida, the Middle Miocene (Badenian) pelites can be considered good quality source rock, mainly gas generating. There are also source rocks of excellent oil generation potential among them. The Badenian carbonates are qualified as fair gas generating source rocks, containing matured organic matter suggesting substantial terrigenous impact. Based on the organic carbon content the Lower Pannonian calcareous marl formations are in great part fair and partly good source rocks. Their organic matter is primarily of Type III. Their thermal maturity is appropriate for the oil generating zone, and intensive generation is possible in the parts of the basin deeper than 2,500 metres. Only one third of the TOC contents in the Lower Pannonian pelite is fair based on the samples analysed, and merely 8% received good or very good quality ranking. The maturity of the definitely autochthonous organic matter corresponds to the oil window. The Upper Pannonian pelitic rocks contain terrigenous organic matter and are immatured. Their average TOC content value is low, and only the maximum levels are acceptable, therefore their HC-potential is also low (HORVÁTH et al. 2011). The source rock of the Zaláta–Dravica natural gas accumulation explored in the eastern part of the Dráva trough probably belongs to the Neogene succession, rich in organic matter and situated in the deeper zones of the Dráva trough (GELLÉRT et al. 2012).

The Rock-eval measurements carried out in the Iharos–1 and Jankapuszta–1 wells suggest that the rock-generated hydrocarbons here must have been from the Lower Pannonian and Middle Miocene argillaceous marls and calcareous marls. They occur in great quantities and in deep structural positions in the Gyékényes–Zákány and the Nagykanizsa deep zones. Based on the geochemical analysis of samples from wells drilled on the structural high stretching from Belezna to Vése, the dry gas generating zone is situated at a depth between 4.2–4.5 km and the oil window are at depths 2.3–3.8 km in the deep zones around the structural high from the north and south. In the dry gas zone there are mainly Karpatian coarse-grained clastic sediments containing little humus (organic matter). The Middle Miocene pelitic sediments are located in the oil window. In the main oil generation phase there are mainly sediments containing sapropelic type organic matter of the lower section of the Lower Pannonian. The sources of carbon dioxide in the reservoirs are volcanics, according to one concept; according to the other, their generation is related to the metamorphosis of the Triassic carbonates of the basement rocks (BERNÁTHNÉ et al. 1997c; TORMÁSSYNÉ et al. 2002a, b; KOVÁCS ZS. ed. 2013). The probable areal extension and maturity of the Middle Miocene source rocks in the southern part of Transdanubia are shown in Figure 4.2.8.

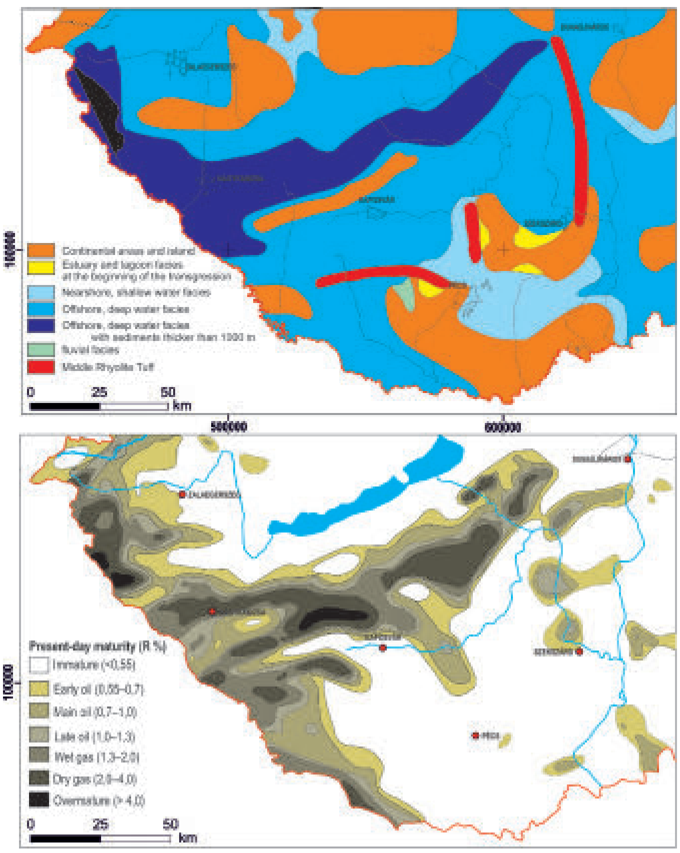


Figure 4.2.8. The suppositional spread (a) (marked in dark blue) and maturity (b) of Middle Miocene source rocks in the southern part of Transdanubia, adapted from BADICS, VETŐ (2012)

Mesozoic carbonates with high organic matter contents may also be considered potential source rocks in South Transdanubia (HORVÁTH et al. 2011). Some Mesozoic formations can also be considered in the Mecsek and the Villány Mountains (BIHARI et al. 1979). The 1–2% vitrinite reflectance values of the Triassic carbonates indicate the main HC generation zone. Maturity of the Lower and Upper Triassic

formations is similar, but with values decreasing towards the east. Their organic matter is predominantly of the huminite type, suitable for generating gas. Somewhat less than half of the samples tested were immature, the others are in the main phase of oil generation and a few in the gas condensate generation phase. Vitrinite reflectance data of the Mecsek type Jurassic rocks (Vasas Marl) refer mainly to the main oil generation phase and to a lesser extent the gas condensate phase. The C_{org} content is much lower in the Jurassic rocks of the Villány than in those of the Mecsek. The Cretaceous rocks in the Mecsek–Villány Unit include the Lower Cretaceous limestone in the main oil generation phase, and the epicontinental Senonian formations in the main oil generation phase and dry gas generation phase. C_{org} contents are basically low, that of the carbonates is sufficient or good, their bitumen content is low, organic matter is of the exinite type. According to T_{max} data they are in the wet gas generation zone (KOVÁCS L. 1995). The genesis of the hydrocarbons originating from the Bóly basin Mesozoic beds can be associated with the Neogene sedimentary cycle and subsidence (BIHARI et al. 1979).

According to BIHARI et al. (1979) it is possible that even the Upper Eocene rocks are source rocks in the Mecsek and Villány Mountains and the surrounding. The Palaeozoic formations are overmature, and their vitrinite reflectance values are high (Carboniferous rocks: R_0: 3.3–3.6%, Permian clastic rocks: R_0: 2.4%). Therefore any hydrocarbons they generated have already migrated away during the intensive denudation phase (JÁRAI et al. 2011).

Reservoir rocks

Due to the complex geological build-up of the Zala–Dráva Basin and the surroundings, the hydrocarbon reservoir rocks also encompass a broad spectrum.

The Zala Basin reservoir rocks are as follows (BERNÁTHNÉ 1997a; VÖLGYI et al. 1985; KŐRÖSSY 1988; GYARMATI 2008; HATALYÁK et al. 2004; JÓSVAI et al. 2001a; TORMÁSSYNÉ et al. 1992; JUHÁSZ, KUMMER ed. 1997; MOLNÁR et al. 1998a, b; 1999a, b; KOVÁCSVÖLGYI et al. 2003b; NÉMETH et al. 2012, 2013a):

— Middle–Upper Triassic carbonates: Sávoly Limestone Formation (?) (Sávoly South field); Igal Formation (Sávoly West field);

— Upper Triassic (Carnian–Norian) Main Dolomite Formation fractured, karstified parts (for instance Nagylengyel, Barabásszeg, Szilvágy, Pusztaapáti fields);

— Upper Triassic (Norian–Rhaetian) Dachstein Limestone Formation fractured, karstified parts (for instance Ortaháza East field);

— Upper Cretaceous (Senonian) Ugod Limestone Formation fractured, karstified zones (for instance Nagylengyel, Szilvágy, Szilvágy South, Szentgyörgyvölgy-Csesztreg fields);

— Basal conglomerates made up of eroded clastics of Ugod Limestone material, starting the Late Cretaceous (Senonian) sedimentary cycle (for instance Szilvágy South field);

— Upper Cretaceous Jákó Marl Formation — gryphaea limestone intercalations (for instance Nagylengyel);

— Upper Cretaceous Jákó Marl Formation — carbonate breccia intercalations;

— Middle Eocene Szőc Limestone Formation karstified layers;

— Middle Miocene (Karpatian(?) – Badenian) volcanic bodies(Horvátkút, Somogysámson fields);

— Miocene (Badenian) Tekeres Schlier Formation, glauconitic sandstone intercalation (for instance Nagylengyel);

— Miocene (Badenian) Lajta Limestone Formation (for instance Barabásszeg, Eperjehegyhát, Horvátkút, Somogysámson, Sávoly South-west fields);

— Miocene (Badenian) Szilágy Clay Marl Formation sandstone layers (Bajánsenye, Őriszentpéter-South fields);

— Lower Pannonian sandstones: Szolnok Sandstone Formation (for instance Ortaháza, Ortaháza East, Zalatárnok, Rádiháza, Gutorfölde, Budafa, Lovászi, Sávoly East fields);

— Upper Pannonian sandstone (Újfalu Formation, Kilimán field).

The porosity of the Triassic carbonates (Main Dolomite Formation, Dachstein Limestone, Ugod Limestone) is merely 1–2.5%; these rocks may be good reservoirs due to secondary porosity caused by tectonic processes and karstification (VÖLGYI et al. 1985, NÉMETH et al. 2012). The porosity of the breccias containing the clasts of the Ugod Limestone and the basal conglomerates deposited in the Senonian sedimentary cycle is 18% (VÖLGYI et al. 1985, LAUKÓ et al. 2004). The Mesozoic carbonates constitute the reservoirs of the accumulations in many cases together with the overlying Badenian "Lajta Limestone". The porosity of the gryphaea-bearing limestone intercalations in the Jákó Marl Formation at Nagylengyel is 2.2%. The karstified layers of the Szőc Limestone Formation at the basin margins form potential reservoirs (NÉMETH et al. 2012).

The porosity of the Badenian glauconitic sandstone (the so-called green sandstone) intercalations in the Tekeres Schlier Formation at Nagylengyel is 15–16%. It is considered here as a marker horizon of the Miocene oil reservoir (VÖLGYI et al. 1985, KŐRÖSSY 1988). Lajta Limestone Formation overlying the Mesozoic basement has good reservoir parameters, in particular where basal conglomerate is also encountered (LAUKÓ et al. 2004), but its rocks accumulate also hydrocarbons irrespective of the basement (for instance Eperjehegyhát field), with a porosity of 5–8.8%, consisting of intergranular and fracture porosity. Porosity of the Lower Pannonian sandstone reservoirs varies in a range of 9–23% (VÖLGYI et al. 1985, NÉMETH et al. 2013a).

The reservoir rocks of hydrocarbons in the Dráva Basin and in South Transdanubia are as follows (GELLÉRT et al. 2006, 2012; HORVÁTH et al. 2011, 2012; JÁRAI et al. 2011; GYARMATI 2008):

— Altered zones of Palaeozoic carbonates and metamorphites (for instance Barcs West field, HHE–Istvándi–2 field);

— Upper Carboniferous Téseny Sandstone Formation: siltstone and claystone intercalations (for instance Homokszentgyörgy field),

— Altered zones of Mesozoic limestones and dolomites;

— Pre-Pannonian Miocene formations (for instance Barcs West);

— Badenian sandstone and carbonate breccia-conglomerate (for instance Zaláta, Vízvár North, Kadarkút fields);

— Badenian lithothamnium limestone, sandstone, (for instance Istvándi);

— Lower Pannonian basal calcareous marl (for instance Darány West);

Lower Pannonian sandstones (for instance Darány, Görgeteg–Babócsa, Heresznye, Homokszentgyörgy fields, Istvándi "Mézes" sandstone reservoir, Csombárd field);

– Upper Pannonian sandstones (for instance Görgeteg–Babócsa field).

In the vicinity of the Mecsek and Villány Mountains, the weathered burial zones of the palaeosurfaces of Palaeozoic and Mesozoic formations, the Carboniferous sandstones and among the Cenozoic formations the Middle Miocene, Karpatian coarse clastic sediments, the Badenian glauconitic sandstone and lithothamnium limestone, and the rocks around the Lower and Upper Pannonian transitional zone are also considered to be reservoirs. The cemented Upper Carboniferous and Permian sandstones have low reservoir capacity, and are presumably able to store natural gas only (BIHARI et al. 1979).

The secondary porosity of fracturing origin in the metamorphic reservoir rocks of the basement is very low (KÓKAI et al. 1987, MHE 2011). The Palaeozoic reservoir rocks in the top zone of the basement at Istvándi consist of molasse-type, mainly fluvial, and subordinately paludal sandstones and shaly rocks alternating with them, the secondary porosity of which has developed over a long term surface exposure. The porosity of Badenian lithothamnium limestones is around 24–28% (MHE 2011). The few percent secondary porosity of the Lower Pannonian calcareous marl is of tectonic origin. The Lower Pannonian sandstones are the most important reservoir rocks in the Dráva Basin, with a porosity of 14–20%. The Upper Pannonian sandstones, with approximately 25% porosity, play a subordinate role as reservoirs (BERNÁTHNÉ et al. 1978, VÖLGYI et al. 1985, MHE 2011).

Migration

The hydrocarbon reservoirs of South Transdanubia — Zala Basin and Dráva Basin — filled up from multiple directions, both along vertical and horizontal migration routes.

Substantial vertical migration can be assumed in the Zala Basin. The migration routes are mainly associated with tectonic components (for instance the CO_2 gas of the Budafa deep reservoir migrated from the basement into the present reservoir along deep faults (KOVÁCSVÖLGYI et al. 2003b), but the fractured zones along the faults also played a significant role in Sávoly (MOLNÁR et al. 1999a)). The best migration pathways are the fractured, brecciated sections of the shear zones and the foliated surfaces along the axial planes of folds (LAUKÓ et al. 2004).

The karstified, fractured surface of the Triassic and Cretaceous carbonates is of significance in terms of migration. Migration that took place along the unconformity along the basement surface was determinative, for instance in the Szentgyörgyvölgy–Csesztreg natural gas accumulation zone (along the unconformity surface of the Upper Cretaceous beds, JUHÁSZ, KUMMER ed. 1997).The main migration horizon was the eroded surface of Mesozoic carbonates on the Ortaháza–Hahót high and in the Lovászi depression (MOLNÁR et al. 1999c). Blocks of Triassic carbonates of higher structural position in the Lovászi depression contain reservoirs as well, including the overlying Badenian lithothamnium limestone (JÓSVAI 2001). The migration was assisted by the unconformity surface formed on the Mesozoic surface in the filling up of the reservoirs in the Sávoly area (MOLNÁR et al. 1999a).

The unconformity surface between the igneous-metamorphic basement complex and the overlying Badenian succession might have played a more subordinated role in terms of migration, since permeability of the magmatites is lower than that of the karstified carbonates.

Both vertical and horizontal migration can be assumed in the Badenian, Sarmatian and Pannonian successions. The horizontal migration accomplished in the Neogene formations along the sequence boundaries and unconformity surfaces must have been significant. The steeply dipping surfaces of strike-slip movements played a priority role in vertical migration towards the Pannonian reservoirs (SZABÓ-HORTI et al. 2012, SZENTGYÖRGYINÉ et al. 2013, NÉMETH et al. 2013a). In the Bajánsenye and Őriszentpéter South natural gas accumulation zone, the primary surface for the fluid flows, originating predominantly from the Badenian rocks, is the contact surface of the Middle Miocene sandstone and argillaceous marl lenses, as well as the listric faults (BERNÁTHNÉ et al. 1997a). In the case of the Budafa field, the hydrocarbons which accumulated in the deeper horizons of sandstones and in the glauconitic sandstone of the Middle Miocene took a shorter migration pathway (MOLNÁR et al. 1999c, KOVÁCSVÖLGYI et al. 2003b).

Reservoirs in the Zala Basin were filled up by multiple-direction migration (JUHÁSZ, KUMMER ed. 1997). Hydrocarbons

might have arrived here from the Őrség depression, the Bak–Nova trough, the Lovászi depression, the Budafa trough and the Kanizsa deep zone (Kőrössy 1988; Molnár et al. 1999a; Jósvai et al. 2001a, b; Németh et al. 2013a). In the Nagylengyel regional oil accumulation zone, the reservoirs filled up along three (northern, middle and southern) migration routes, in at least three stratigraphic horizons (Upper Triassic limestone and dolomite, and two horizons of the Upper Cretaceous succession) (Juhász, Kummer ed. 1997). Hydrocarbons of the Ortaháza–Kilimán basement high oil and gas accumulation zone were formed predominantly in the Lovászi depression; however, the reservoirs may have been filled up from the north, i.e., the Bak–Nova trough, as well. Lesser amounts of hydrocarbons arrived to the basement high from the Budafa basin (located to the south) by north-eastward migration. (Molnár et al. 1999b). The relatively high density oils around the Zalakaros–Sávoly fields were generated in the Kanizsa deep zone and migrated to the north and from the southern part of the Zala Basin to the NE (Molnár et al. 1999a). In the Buzsák and Tatárvár field areas, hydrocarbon migration might have occurred through the tectonic zone of NE–SW direction, from the deep zone to the lithothamnium limestone reservoirs (Keresztes et al. 2014).

In the Dráva Basin, the presence of different quality hydrocarbons indicates multiple-direction migration, since the various source rocks generated hydrocarbons of different quality and since subsidence of the basin also had a role in the migration process. The main migration route went from the deeper parts of the Dráva Basin to the north and north-east, and it is likely that significant lateral and vertical migration occured. Both the basement morphology and the characteristics of the fluids in the reservoirs on the Croatian side of the state border (Molve, Kalinovac, Stari Gradac) confirm this migration direction (Horváth et al. 2011); in this way, a great quantity of hydrocarbon could have filled the Hungarian side reservoirs as well. Hydrocarbons might have migrated along additional routes but migrated mainly in the horizons of Pannonian sandstones and along the fault systems which became functional in the Pannonian age (for instance Vízvár–Heresznye fields). Faults could have played a significant role also in trapping. The highly permeable breccia–conglomerate rocks overlying the Palaeozoic and Mesozoic basement provide favourable conditions for migration. The source of the gas condensates of the Vízvár North field is not yet clarified, but it can be assumed that they could have got to their location of accumulation from the SW, on the migration path between the Ferdinandovec–Vízvár and Felsőgóla–Somogyudvarhely basement highs. (Gellért et al. 2006). Direct migration can be assumed in the contact zone of the source rock and the carbonate–clastic reservoirs (Gellért et al. 2012), for instance in the case of the Zaláta gas field.

The unconformity surfaces between the Palaeo-Mesozoic basement and the overlying Neogene formations, and also the unconformity between the pre-Pannonian Miocene and the Pannonian succession should also be considered as migration paths (Bernáth et al. 1978). Geochemical data suggest that secondary migration took place in the Late Miocene following the formation of the traps (Járai et al. 2011, MHE 2011): oils in the Lower Pannonian reservoirs of the Darány field, for example, couls have accumulated as a result of the vertical migration of the deeper occurring oils in Middle Miocene and Lower Pannonian reservoirs (Bernáth et al. 1978).

Beside the primary migration route of W–E direction, migration could have occurred both from the north and from the south on the Semjénháza–Nagyrécse basement high range as well (Bernáthné et al 1997c). In the Belezna–Mezőcsokonya oil and gas accumulation zone, the unconformity surfaces in the Miocene succession and the base of Miocene may have worked as migration routes, and the Triassic and Miocene reservoirs could have filled up this way, while in the filling of the reservoirs in the Pannonian succession, tectonic surfaces and fracture zones may have played an important role (Molnár et al. 1998d). Due to the regionally southward-sinking basement in the Mezőcsokonya area, the migration of hydrocarbons took place mainly in northern direction, but in the smaller sub-basins, locally, other directions could have developed as well (Szabó, Csizmeg 2013).

The migration routes in the surroundings of Mecsek and Villány Mountains developed primarily along the Mesozoic and Palaeozoic basement surfaces, in the Lower Pannonian sandstone zones, and along the surfaces of the thrust faults. The migration of water and gas was directed from south to north in the East Mecsek area (Bihari et al. 1979).

The prevailing oil density versus depth relationship in the Zala region is that generally lighter oils are in a shallower position. On a field scale, the relationship is that the shallower the depth, the greater the oil density. The deeper the average depth where migration is taking place, the stronger is the tendency of inversely proportional change of oil density with depth. This suggests that the primary segregation process was a kind of separation mechanism according to carbon-chain length through semi-permeable sediments. Overflow mechanism is indicated by the density distribution of crude oils. The increasing density with decreasing depth trends occurs only locally and suggests tertiary migration mechanisms within earlier formed reservoir groups, in which the individual reservoirs within a group were hydraulically connected to each other (Kovács Zs., Zilahi 2018).

Traps

Stratigraphic and lithologic traps occur in the pre-Pannonian Miocene (mainly Badenian) and in the Pannonian successions, while in the basement primarily the structural and lithologic traps and their combinations are typical (Figure 4.1.7). The structural traps are found in connection with the strike-slip movement zones, associated with antithetic, listric

faults, or anticline structures (LAUKÓ et al. 2004). Hydrocarbon fluids of the Triassic – Middle Miocene reservoirs were trapped in the elevated central zones of positive flower structures in the Ortaháza–Kilimán basement high ridge and around the Sávoly–Zalakaros fields (SZABÓ-HORTI et al. 2012). Reservoirs of the Nagylengyel and Szilvágy fields were formed in high structural position Mesozoic blocks. Further migration of hydrocarbons was prevented by stratigraphic traps developed under the Mesozoic–Miocene unconformity surface and along the boundary of the Upper Cretaceous Polány Marl (seal) and Ugod Limestone Formation (reservoir) (VÖLGYI et al. 1985, TORMÁSSYNÉ et al. 1992).

Lithologic traps are associated with lithological changes, or decreased permeability (for instance Bajánsenye field) (LAUKÓ et al. 2004). The Pannonian accumulations were formed in large amplitude anticlines (Lovászi), and above the basement highs, in slightly domed traps (Budafa–Oltárc), but closure of lithological nature is also known to have occurred: changes of porosity/permeability formed traps, as for instance in the Lower Pannonian reservoirs of the Budafa–Kiscsehi field (SZABÓ-HORTI et al. 2012, SZENTGYÖRGYINÉ et al. 2013). Lithological traps were formed in the Bak–Nova trough at Zalatárnok above the strongly fractured Eocene formations, and in the Lower Pannonian sandstone beds of the Neogene sequence (VÖLGYI et al. 1985).

In the Dráva Basin structural–lithologic traps are found in the Mesozoic reservoir, combined structural–stratigraphic traps in the Miocene formations, and typically lithologic–structural traps in the Pannonian succession (GELLÉRT et al. 2012). The formation of most traps might have been started in the Middle Miocene post-rift phase, and the evolution of the structural traps can be partly associated with the inversion movements of the Pannonian compression phase (MHE 2011). As the reservoir geological conditions are complicated, the exploration of so called hidden traps might be advantageous (such traps might include for instance those related to the pinching-out sandstone and conglomerate layers, reservoirs connected with the Pannonian delta/pro-delta alluvial cones, Pannonian turbidite sandstone zones, "slump" bedsets associated with slides, and the reverse faults in compressional structural zones of the metamorphic and carbonate formations in the Palaeozoic–Mesozoic basement, etc. (RUMPLER 1998).

In the vicinity of the Mecsek and Villány Mountains, the traps could have been formed in the elevated zones of compression structures and in the beds pinching-out on the margins of the depressions (BIHARI et al. 1979).

Seal rocks

The seal rocks (cap rocks) of the Mesozoic and Middle Miocene reservoirs in the area are mainly the Lower Pannonian marls and argillaceous marls (Endrőd Marl Formation). In some places in the Lower–Middle Miocene and the Upper Cretaceous marls, pelites also form a seal (VÖLGYI et al. 1985, NÉMETH et al. 2012, SZABÓ-HORTI et al. 2012). In certain areas (for instance, the Hahót–Pusztaszentlászló field) Sarmatian pelites capped the reservoir formed in the Triassic basement or in Badenian lithothamnium limestone. The several-metres thick argillaceous marls separating the sandstones within the Pannonian sequences are impermeable under the current hydrostatic pressure conditions; and therefore behave as caprocks.

In the case of the Nagylengyel field, the Kössen and Jákó Marl Formations and the Polány Marl Formation act as seals overlying the Main Dolomite Formation and the Ugod Limestone Formation, respectively (KOVÁCSVÖLGYI et al. 2003c).

In the Dráva Basin and its surroundings, the seal rocks of the Palaeozoic, Mesozoic and Miocene reservoirs are mainly the Lower Pannonian marls, the argillaceous marls, and also the Middle Miocene marls, which act as cap rocks. In the Pannonian formations, the several-metre thick argillaceous marls — which separate the sandstones, the mainly shales and the shaly rocks which are impermeable under the given hydrostatic pressure conditions — create the cap rocks (GELLÉRT et al. 2012, MHE 2011, HORVÁTH et al. 2011). The lateral closure might be caused by lithological change or tectonic components as well. Lower Pannonian seal rocks can also be considered in the Bóly sub-basin (BIHARI et al. 1979).

Hydrocarbon fields of South Transdanubia — Zala and Dráva Basins

Data characterising the discovered reservoirs (hydrocarbon composition, calorific value, etc.) was mostly derived from the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ), in other cases the source is indicated.

Bajánsenye. The natural gas occurrence was discovered in 1986 with the Baján–1 well, which explored two narrow reservoirs containing combustible gas in Badenian formations. By the end of the 1980s three further wells explored the gas accumulation (Baján–2, –5, –6). The Baján–7 well completed in 1991 discovered good quality gas and condensate in Upper Badenian sandstone (Szilágy Marl Formation) (TORMÁSSYNÉ et al. 1992, JUHÁSZ, KUMMER ed. 1997). The combustible part of the gas was 97.9%, the calorific value was 38 MJ/m^3, the methane content (CH_4) was 86.5%, the carbon dioxide content (CO_2) 1.7%, the nitrogen content (N_2) 0.4%, and the C_{5+} content (hydrocarbon compounds with more than five carbon atoms) was 0.3 g/m^3.

Bajcsa. The single reservoir developed in the (domed) traps combined with lithologic changes in a Neogene pseudoanticline above the Mesozoic basement. Eight free gas reservoirs were located in the Lower Pannonian sandstone (AP–3–7b). The

combustible part of the gas was 96.1%, the calorific value 35.3 MJ/m^3, CH_4 94.4%, CO_2 1.5%, N_2 2.4%, and C_{5+} 8.3 g/m^3. The density of the condensate was 759.8 kg/m^3 (Völgyi et al. 1985).

Barcs. A free gas reservoir with condensate is situated in the Mézes horizon discovered by the HHE–Istvándi–1 well (2009), formed in Lower Pannonian sandstone (MHE 2011). The combustible part of the gas accumulated in the tectonically closed single reservoir was 88.6%, the calorific value 35.4 MJ/m^3, CH_4 79.3%, CO_2 0.6%, and N_2 10.8%. It also contained 43.1 g/m^3 gas condensate. An oil and a gas reservoir were detected in two additional horizons in the Barcs area (Alma-D and Alma-D gas cap).

Barcs West (Barcs-Nyugat in Hungarian). The natural gas occurrence was discovered by the Barcs-Ny–1 well in 1979. The reservoir was formed on the top of a flat domed structure in Barcs. The high condensate and high hydrogen sulphide (H_2S) containing a multiple gas reservoir is predominantly situated in the Palaeozoic–Precambrian carbonate and metamorphic, and subordinately in the Middle Miocene (Badenian) rocks (Kőrössy 1989, Juhász, Kummer ed. 1997). The gas-water contact (GWC) of the accumulation is at 3,860 metres below sea level (m bsl), the combustible part of the gas 87.9%, the calorific value is 38.1 MJ/m^3, CH_4 74.7%, CO_2 11.0%, N_2 1.1%, C_{5+} 45.7 g/m^3.

Belezna. The occurrence was discovered in 1963 by the Be–2 well where hydrocarbons accumulated in stratigraphic and lithologic traps formed in the domed Neogene structure. The reservoir rock consists of Badenian calcareous sandstone, conglomerate (Lajta Limestone Fm), Sarmatian age sandstone (Kozárd Fm) and Lower Pannonian sandstone (Szolnok Fm). The oil is of intermediate type (Völgyi et al. 1985).

— *AP–1–2–3–4–5 natural gas reservoirs*: single reservoirs situated in Lower Pannonian reservoir rocks. The GWC is at 1,861–1,813 m, the combustible part of the gas is 76.8–96.4%, the calorific value is 31.0–40.6 MJ/m^3, CH_4 70.8–74.2%, CO_2 2.4–6.2%, N_2 1.2–17%. The condensate content is 16.4–25.3 g/m^3. The density of the condensate is 798 kg/m^3 (Völgyi et al., 1985).

— *Miocene–2, Miocene–3 reservoirs* of Be–4, Be–29 wells (4 reservoirs): the OWC is at 2,110–2,097 m bsl, the density of intermediate oil is 799–848 kg/m^3. The combustible part of the dissolved gas is 96.2–97.5% (Völgyi et al 1985), the calorific value is greater than 40 MJ/m^3.

Belezna South (Belezna-Dél). Two free gas reservoir and one oil reservoir belong to this field.

— *Be2M reservoir:* the small free-gas reservoir of the Be–22 well can be found in Middle Miocene calcareous sandstone and fine-grained siltstone reservoir rocks. The GWC is at 2,100 m bsl, the combustible part of the gas is 96.8%, the calorific value is 38.4 MJ/m^3, CH_4 86.5%, CO_2 2%, N_2 1.2%, C_{5+} 1.2 g/m^3.

— *Be8M reservoir:* the free gas reservoir of the Be–28 well. The reservoir rock is calcareous sandstone, conglomerate and siltstone beds below the Badenian lithothamnium marl, calcareous marl horizon (Németh et al. 2013b). The GWC in the free gas reservoir is at 2,435 m bsl, the combustible part of the gas 98.3%, the calorific value is 42.5 MJ/m^3, CH_4 83.0%, CO_2 1.1%, N_2 0.6%. C_{5+} 3 g/m^3.

The density of the condensate in the gases of Be–22 and Be–28 wells are of intermediate type, the density is 766.6–773.9 kg/m^3.

— *Be5M reservoir:* the dissolved gas containing oil reservoir of the Be–25 well. The reservoir rock is made up of the alternating layers of calcareous sandstone and fine-grained sandy calcareous marl (Németh et al. 2013b). The oil-water contact (OWC) in the reservoir is at 2,100 m bsl, the density of the intermediate oil is 800 kg/m^3. The dissolved gas content is 300 m^3 gas/m^3 oil, the combustible part of the gas is 97.4%, calorific value is 39.6 MJ/m^3, CH_4 84.6%, CO_2 2%, N_2 0.6%.

Belezna East 1 Deep Level (Belezna-Kelet–1 mélyszint). Before the structure was drilled, it was detected through integrated seismic interpretation by the Mol Plc. The reservoir was formed in a structural trap, the reservoir rock is brecciated Triassic dolomite and limestone, on the basis of the seismic correlation and facies analysis. (Németh et al. 2013b).

Belezna East 1 (Belezna-Kelet–1). The occurrence was discovered by the Be.K–1 well (2013) in Miocene sandstone. The reservoir is in the same geological environment as the neighbouring Őrtilos I–IV reservoirs (Németh et al. 2013b). The "*Belezna East Miocene*" dissolved gas containing oil reservoir was located here, and the dissolved gas content is 295 m^3/m^3.

Belezna East 2. The Be.K–2 well (2012) discovered two free gas reservoirs in Lower Pannonian sandstone. In the Lower Pannonian 1 and Lower Pannonian 2 reservoirs the GWC is 1,948–1,940 m bsl, the combustible part of the gas is 79.6%, the calorific value is 31.4 MJ/m^3, CH_4 72.7%, CO_2 2.2%, N_2 18.1%, C_{5+} 52.9 g/m^3.

Berzence. The Ber–2 well discovered combustible and inert mixed gas and condensate in Badenian biogenic limestone (Lajta Limestone Fm), and also discovered combustible gas in Lower Pannonian sandstone (Gellért et al. 2006).

Budafa–Kiscsehi. The crude oil and natural gas occurrence was discovered by the B–1 well drilled in 1936. Hydrocarbons are accumulated in traps formed by dome-forming,, lithological and tectonic closing in a Neogene anticline above the deep basement complex. Several oil and gas reservoirs were located in the field in multiple horizons (Borsfa, Sziget, Zala–Kerettye, Lower Lispe, Upper Lispe, Zala, Budafa–Kiscsehi, Szintfeletti reservoir horizons). Reservoirs were formed in the sandstone layers of the Lower Pannonian beds (Szolnok Formation) (Völgyi et al. 1985).

— *Borsfa horizon:* Three oil reservoirs with gas cap were located. The OWC is 1,270 m bsl, the density of the intermediate oil is 799.8 kg/m^3, the sulphur content of the oil is 0.2%. The dissolved gas content is 135 m^3/m^3, the combustible part is

98.2%, the calorific value of the gas is 40 MJ/m^3 (VÖLGYI et al. 1985). The combustible part of the cap gas is 95.8%, the calorific value is greater than 40 MJ/m^3. The C_{5+} content is 80 g/m^3.

— *Sziget horizon:* Three undersaturated oil reservoirs were located in the Lower Pannonian sandstone reservoir, the OWC is at 1,127–1,090 m bsl, the density of the intermediate type oil is 842 kg/m^3 (VÖLGYI et al. 1985). The dissolved gas content is 102 m^3/m^3, the combustible part of the gas is 99.5%, and the calorific value is greater than 40 MJ/m^3. The C_{5+} content is 160 g/m^3.

— *Lower Lispe horizon:* Four dissolved gas containing oil reservoirs and three gas reservoirs were located in this horizon. In the oil reservoirs the OWC is 995 m bsl, the density of the intermediate oil is 832 kg/m^3 (VÖLGYI et al. 1985), the sulphur content of the oil is 0.2%. The dissolved gas content is 98 m^3/m^3, the combustible part is 99.5%, the calorific value is 40 MJ/m^3. In the three natural gas reservoirs the GWC is at 975–1,007 m bsl, the combustible part of the gas is 92.6%, the calorific value is 40 MJ/m^3 (VÖLGYI et al. 1985).

— *Upper Lispe horizon:* Eight oil reservoirs with gas cap, 6 unsaturated oil reservoirs with dissolved gas and 3 free gas reservoirs were located in the Lower Pannonian sandstones. The OWC in the oil reservoirs with gas cap is at 971–945 m bsl, the density of the intermediate oils is 820 kg/m^3. The combustible part of the cap gas is 99.5%, the calorific value is 42.3 MJ/m^3. The C_{5+} content is 200 g/m^3. In the 6 undersaturated oil reservoirs the OWC is at 990–945 m bsl, the intermediate oil density is 824 kg/m^3. In the free gas reservoirs the GWC is at 975–945 m bsl. The combustible part of the gas is 99.5%, the calorific value is 42.3 MJ/m^3.

— *Zala–Kerettye horizon:* Five undersaturated oil reservoirs in the Kerettye horizon, and 7 undersaturated oil reservoir and 1 oil reservoir with gas cap in the Zala horizon were located in the Lower Pannonian sandstones (VÖLGYI et al. 1985), the average OWC in the deposits is 893 m bsl, the density of the intermediate oil is 820 kg/m^3. The sulphur content of the oil is 0.2%. The gas parameters are as follows: the combustible part is 99.5%, the calorific value is 42.3 MJ/m^3. The C_{5+} content is 168.8 g/m^3.

— *Budafa–Kiscsehi horizon:* 5 free gas reservoirs, 10 oil reservoirs with gas cap and 1 undersaturated oil reservoir were located in Lower Pannonian sandstones. The GWC in the free gas reservoirs is at 872–870 m bsl, the combustible part of the gas is 97.6%, the calorific value is 43.6 MJ/m^3, CH_4 81.5%, CO_2 0.8%, the C_{5+} content is 210 g/m^3 (VÖLGYI et al. 1985).

In the oil reservoirs with gas cap, the OWC is at 851–842 m bsl, the density of intermediate oil is 810–822 kg/m^3. The combustible part of the cap gas is 97.6%, the calorific value is 43.6 MJ/m^3, CH_4 81.5%, CO_2 0.8%, C_{5+} 208 g/m^3.

In the oil reservoir the OWC is at 832 m bsl, the density of intermediate oil is 820 kg/m^3. The combustible part of the dissolved gas is greater than 95%, the calorific value is greater than 40 MJ/m^3 (VÖLGYI et al. 1985).

— *Szintfeletti horizon oil reservoir:* the OWC is 827 m bsl, the density of intermediate oil is 800 kg/m^3.

Budafa Deep Level (Budafa mélyszint): The CO_2 rich free gas reservoir was discovered by the B–III well in 1966. The gas accumulated in a combined structural/stratigraphic trap which formed in the basal breccia and conglomerate layers of the Lajta Limestone Formation and in the topmost section of the carbonate beds belonging to the pre-Cenozoic basement (Táska Limestone Formation), in the lower part of the Neogene anticline structure triggered by folding. The GWC is at 3,120 m bsl (VÖLGYI et al. 1985), the CO_2 content of the gas is 81%; thus, the calorific value is very low as well: 6.1 MJ/m^3. The CH_4 content is 15.8%, the N_2 content is 2.3%.

Budafa–Oltárc. The natural gas field was discovered by the BO–5 well in 1975. The gas is accumulated in Lower Pannonian sandstone (Budafa [BO–5 well] and Szintfeletti horizon [BO–3 well]) (VÖLGYI et al. 1985).

— *Budafa free gas reservoir:* the GWC is at 1,125 m bsl, the combustible part of the gas is 96.7%, the calorific value is 35.2 MJ/m^3, CH_4 95.8%, CO_2 2.3%, N_2 1%,C_{5+} 5 g/m^3.

— *Szintfeletti free gas reservoir:* the GWC is at 865 m bsl, the combustible part of the gas 98.4%, the calorific value is 35.6 MJ/m^3, CH_4 97.95%, CO_2 0.4%, N_2 1.2%, C_{5+} 2.2 g/m^3.

The gas in the two reservoirs provides intermediate type condensate as well; its density is 808 kg/m^3.

Buzsák. The oil reservoir formed in Miocene (Badenian) lithothamnium limestone was discovered in 1954 by the Bu–1 well (VÖLGYI et al. 1985). The OWC is 513 m bsl. The density of the naphthenic oil is 950 kg/m^3.

Csesztreg. The free gas field was discovered by the Cse–I well in 1978. The GWC in the reservoir developed in Upper Cretaceous breccia and limestone succession (Ugod Limestone Formation) is at 3,622 m bsl. The combustible part of the gas is 51.2%, the calorific value is 20.2 MJ/m^3, CH_4 48.2%, CO_2 43%, N_2 5.8%, C_{5+} 82.9 g/m^3. The condensate is paraffinic type, and its density is 779.5 kg/m^3.

Csombárd. The Csom–1 well was completed in 1997 and discovered four small sized gas accumulations (AP–I–IV reservoirs) in Lower Pannonian sandstone and one in Middle Miocene Badenian limestone (Lajta Limestone Fm). Reservoirs were formed in a pseudoanticline structure, and the closure is lithological. (MOLNÁR et al., 1998c). The GWC in the *Badenian limestone gas reservoir* is at 1,990 m bsl, the combustible part is 60.98%, the calorific value is 26.4 MJ/m^3. Its CH_4 is 53.5%, CO_2 32.9%, N_2 6.1%, C_{5+} 50.5 g/m^3. The GWC in the four *Lower Pannonian free gas reservoirs* is in a range of 1,837–1,748 m bsl. The combustible part of the AP–I + AP–II reservoirs' gas is 96%, the calorific value is 33.4 MJ/m^3, CH_4 94.7%, CO_2 1.5%, N_2 2.5%, C_{5+} 4.6 g/m^3.

Darány. The oil and gas field was discovered by the Dar–1 well in 1975. Hydrocarbons were accumulated above a

Miocene Badenian basement high structure in a slightly dipped pseudoanticline. The trap is lithologically closed, and the reservoir rock is Lower Pannonian sandstone (VÖLGYI et al. 1885).

— *Darány–1 free gas reservoir:* The GWC is at 1,867 m bsl, the combustible part of the gas is 45.6%, the calorific value is 19 MJ/m^3, CH_4 40.2%, CO_2 15.3%, N_2 39.2%, C_{5+} 20.9 g/m^3. The density of the condensate is 736.9 kg/m^3 (VÖLGYI et al. 1985).

— *Darány–2 and –3 oil reservoirs* with dissolved gas: The OWC is at 1,455–1,435 m bsl. The density of the paraffinic oil is 820 kg/m^3. The dissolved gas content is 80 m^3/m^3. The combustible part of the gas is 95.8–95.9%, the calorific value is 52.7–64 MJ/m^3. The CH_4 content is 52.8–67.4%, CO_2 0.84–0.85%, N_2 2.3–3.4%. The gas contains 172.4–174.7 g/m^3 condensate.

Darány West (Darány-Nyugat). An oil occurrence was discovered by the Dar.Ny–1 well (1978). The multiple reservoir was developed on the top of the Middle Miocene Badenian carbonates (Lajta Limestone Formation) and in the base of the Lower Pannonian calcareous marl. The purpose of drilling the Dar.Ny–2 well (1980) was to explore the oil reservoir in a higher structural position. The secondary porosity of the calcareous marl is of tectonic origin. The oil is of intermediate type, its density is 878.1–884.9 kg/m^3 (MHE Kft. 2011). Sulphur content of the oil is 0.4–0.5%.

Eperjehegyhát. The undersaturated *oil reservoir E3, 6M* was discovered on the basis of well geophysical data reevaluation of the wells E–3 (1972) and E–6 (1986). The single reservoir lies in Middle Miocene Badenian lithothamnium beds (Lajta Limestone Fm). The density of the intermediate oil is 860–910 kg/m^3. The dissolved gas contain 95% methane, the calorific value is 31.4 MJ/m^3 (NÉMETH et al. 2013a).

Görgeteg–Babócsa. The hydrocarbon field was revealed by the GB–2 well in 1954. Hydrocarbons were accumulated in the stratigraphic and lithologic traps formed in a Neogene pseudoanticline above the Precambrian metamorphic basement high ridge. Most of the reservoirs contain combustible natural gases; the oil reservoirs (GB–5. Lower Pannonian and GB–15. Upper Pannonian) are of secondary importance (VÖLGYI et al. 1985).

— *GB–4–14 twelve free gas reservoirs:* The GWC in the Lower Pannonian reservoir is at 1,774.5–1,116 m bsl, the combustible part of the gas is in a range of 66.4–85.7%, the calorific value is between 30–40.5 MJ/m^3, CH_4 56.5–76%, CO_2 1.2–27.7%, N_2 4.2–16.5%, C_{5+} 25–59 g/m^{3}range. The density of the paraffinic type condensate is 729.2 kg/m^3 (VÖLGYI et al. 1985).

— *GB–5 reservoir:* undersaturated oil reservoir formed in the Lower Pannonian succession. The OWC is at 1,755 m bsl, the density of the intermediate oil is 760 kg/m^3. The dissolved gas content is 50 m$^{3/}$m^3. The combustible part of the gas is 92.4%, the calorific value is 41.9 MJ/m^3.

– *GBK reservoir:* free gas reservoir in the eastern field section (Görgeteg–Babócsa East, GBK) which was discovered by the GBK–2 well in 1960. The GWC in the Lower Pannonian reservoir rock is at 2,009 m bsl, the combustible part of the gas is 84.0%, the calorific value is 37.9 MJ/m^3. CH_4 72.89%, CO_2 8.24%, N_2 4.2–16.5%, C_{5+} 0.9 g/m^3. The condensate is of paraffinic type, its density is 728–804.5 kg/m^3.

– *GB–15 reservoir*: the undersaturated oil reservoir was located in Upper Pannonian sandstone. The OWC is at 881.5 m bsl, the density of the intermediate oil is 760 kg/m^3. The dissolved gas content is 82 m^3/m^3 The combustible part of the gas is 92.4%, the calorific value is greater than 40 MJ/m^3 (VÖLGYI et al. 1985). The CH_4 61%, CO_2 1.6%, N_2 6%.

Gutorfölde. The natural gas field was discovered by the Gutorfölde–1 well (2011). Four free gas reservoirs were explored in stratigraphic traps of Lower Pannonian formations. The reservoir rock is composed of alternating thin layers of turbidite sandstone, aleurolite and argillaceous marl. Traps were formed in the turbidite channels and lobes. Three free gas reservoir and one gas reservoir with condensate were located. The combustible part of the gas in the main reservoir is 91%, the N_2 is 8.5% and the calorific value is 35 MJ/m^3 (NÉMETH et al. 2013a).

Hahót–Ederics. The oil and natural gas occurrence was discovered by the H–30 well in 1945.

— *Hahót–Ederics* undersaturated oil reservoir ("reservoir of He–82 well"): hydrocarbons were accumulated in stratigraphic traps formed on the top of the structural high of the Mesozoic basement. The OWC in the multiple reservoirs is 1,445 m bsl, the density of paraffinic oil is 870 kg/m^3. The dissolved gas content is 18.1 m^3/m^3, the combustible part of the gas 36.2%, the calorific value is 16 MJ/m^3.

— *Nova* natural gas reservoirs: gases were accumulated in stratigraphic/lithologic traps in Lower Pannonian sandstone (Szolnok Fm.). Two reservoirs, the "Lower Nova" and "Upper Nova" were distinguished.

– *Lower Nova:* the GWC in the free gas reservoir is at 1,295 m bsl, the combustible part of the gas is 82.9%, the calorific value is 32.8 MJ/m^3, CH_4 74.7%, CO_2 1.4%, N_2 15.7%.

– *Upper Nova:* the GWC is at 1,254 m bsl, the combustible part of the gas 92.5%, the calorific value is 36.5 MJ/m^3, CH_4 84.2%, CO_2 1%, N_2 6.5%.

All the gas of Lower Nova and Upper Nova reservoirs was recovered, and from the mid-1970s reservoirs have only been used for gas storage (Pusztaederics underground gas storage) (VÖLGYI et al. 1985).

Heresznye. The oil and gas field was discovered by the Her–1 well in 1957. Hydrocarbons accumulated in lithological traps situated in a pseudoanticline above the metamorphic basement high. The reservoir rock is Lower Pannonian sandstone (VÖLGYI et al. 1985).

— *Szinttáj alatti reservoir:* free gas reservoir, the GWC is at 2,235 m bsl. The combustible part of the gas is 15.8%, the calorific value is 7 MJ/m^3. The density of the paraffinic type condensate is 813 kg/m^3.

— *Her–1, –3, Víz–1, Szintfeletti–3 reservoirs:* undersaturated oil reservoirs. The OWC is at 1,788–1,269 m bsl. The

paraffinic-intermediate type oil's density is 790–860 kg/m^3, the sulphur content 0.3%. The dissolved gas contents are 40–100 m^3/m^3, the combustible part of the gas is 39.6–85%, the calorific value is 31.8–38.1 MJ/m^3. The C_{5+} content is 80–153 g/m^3.

— *Her–2, Szintfeletti–1, –2, –4, –5 reservoirs:* free gas reservoirs. The GWC is at 1,868–1,245 m bsl, the combustible part of the gases is 77–88.2%, the calorific value is 33.6–41.1 MJ/m^3. The condensate is of paraffinic, its density is 779–792 kg/m^3 (VÖLGYI et al. 1985).

Homokszentgyörgy. The oil and gas occurrence was discovered by the Hom–1 well in 1979. Three reservoirs were located, one oil reservoir in the Palaeozoic basement rocks; one undersaturated oil reservoir and one free gas reservoir situated in Lower Pannonian sandstone.

— Homokszentgyörgy–1 *Upper Carboniferous reservoir:* the reservoir rock is conglomerate (Téseny Sandstone Fm) with aleurite and shale intercalations. The density of the paraffinic oil is 883 kg/m^3, the sulphur content of the oil is 1.3%.

— Homokszentgyörgy–1 *Lower Pannonian free gas reservoir:* the combustible part of the gas 69.6%, the calorific value is 34.4 MJ/m^3.

— Homokszentgyörgy–1 *Lower Pannonian oil reservoir*: the oil is of intermediate type, its density is 861 kg/m^3.

Horvátkút. The natural gas reservoir of the field was discovered by the Horvátkút Horv–1 well drilled by Blue Star '95 Ltd in 2007. Combustible gas and condensate were located in Badenian "Leitha" sandstone–marl sequence, and in the Karpatian volcanics (GYARMATI 2008). The combustible part of the gas is 81.7%, the calorific value is 32 MJ/m^3, CH_4 74.5%, CO_2 0.4%, N_2 17.9%.

Iharosberény Iharos–2. Several gas horizons were detected in the sequence drilled by the Ih–1 well in 1991, but the test results suggested unfavourable reservoir properties. The Ih–2 well drilled in 1999 discovered commercial combustible gas and industrial grade combustible natural gas in the Lower Pannonian beds. The wellbore traversed four thin, gas-saturated sandstone layers, the "*Lower Pannonian 1–4 gas reservoirs*". Traps are lithologically closed, structural form unknown. Reservoirs belong to the same hydrocarbon system, but constitute a separate hydrodynamic system separated with caprocks. The free gas reservoirs are of a lenticular form (TORMÁSSYNÉ et al. 2002b). The GWC is at 1,374 m bsl, the combustible part of the gas 77.4%, the calorific value is 30.4 MJ/m^3, CH_4 67.7%, CO_2 3.7%, N_2 21.7%.

Inke–Iharosberény–Vése. The Inke occurrence was discovered by the I–1 well back in 1936. The natural gas field can be found in the SW–NE direction elongated area of the Inke basement high. Reservoirs situated in Lower Pannonian silty sandstone (Szolnok Formation Tófej Member) and Upper Pannonian sandstone (Újfalu Sandstone Fm) were located in stratigraphic/lithologic traps of a pseudoanticline formed above a basement high structure (VÖLGYI et al. 1985). Small sized gas reservoirs are sand lenses in Inke, the gas composition in general is unfavourable (KŐRÖSSY 1989). In the Iharosberény Ib–1 well (1963) two Lower Pannonian inert rich mixed gas accumulation were found; in the Ib–2 well, only gas traces were detected (BERNÁTHNÉ et al. 1997c). *Lower Pannonian free gas reservoirs* are known from the Vése Vé–2 well (1964). Fourteen reservoirs are recorded at the Inke–Iharosberény–Vése field. The free gas reservoirs of the ten Lower Pannonian reservoir horizons were discovered by the I–1, I–13, Ib–1 and Vé–2 wells. The GWC in the reservoirs is 1,217.5–1,032 m bsl. The combustible part of the gas is 16.3–28.6%, the calorific value is 12.9 MJ/m^3, its methane content is lesser than 25.7%, CO_2 64.6–79%, N_2 4.7–10.6%, the C_{5+} contents are low, less than 2.5 g/m^3.

In the four *free gas reservoirs of the Upper Pannonian succession* the GWC is 790–638 m bsl, the combustible part of the gas is 28.1–62.6%, the calorific value is 11.5–30.6 MJ/m^3, CH_4 25.8–63.1%, CO_2 13.4–62%, N_2 9.8–17.7%, C_{5+} 0.43–1.32 g/m^3.

Jankapuszta. The Jp–1 well discovered the oil occurrence, and was drilled in 1995. Oil accumulation was found in the top zone of the Middle Miocene calcareous marl, limestone (JUHÁSZ, KUMMER ed. 1997, TORMÁSSYNÉ et al. 2002a). The OWC in the reservoir is 2,277 m bsl. The density of the intermediate oil is 840 kg/m^3, the sulphur content is 0.26%, the combustible part of the dissolved gas is 91%, the calorific value is 55.6 MJ/m^3

Jánosmajor. Crude oil indications were observed in several horizons in the Jánosmajor–3 well drilled by the Magyar Horizont Energia Kft (Hungarian Horizon Energy Ltd) in 2012.

– *Badenian–Palaeozoic reservoir:* the Palaeozoic reservoir opened up at a depth of 1,869–1,877 m bsl, and provided intermediate oil containing little dissolved gas. The density of the oil is 865.3 kg/m^3. The oil produced from Middle Miocene Badenian reservoir came from 1,735–1,788 m bsl in three sections which coincided with that from the Palaeozoic reservoir (SZABÓ et al. 2013a).

– *"Mézes" Lower Pannonian reservoir*: the reservoir rock is a part of a larger sandstone succession in a north–south direction in which the "Mézes" sandstone horizon reservoir produce strong gas peaks in the Jánosmajor–3 well at the 1,525–1,580 m level, according to geophysical logging (SZABÓ et al 2013a). The dissolved gas containing oil is of intermediate type; its density is 828 kg/m^3. The dissolved gas content is 67.3 m^3/m^3.

Kadarkút. The oil occurrence was discovered by the Kkút–2 well in 1981. Oil and some natural gas accumulated in the sand and conglomerate layers in the upper part of the Middle Miocene Badenian sequence (KŐRÖSSY 1989). The OWC is at 770 m bsl. The density of paraffinic oil is 860 kg/m^3.

Kilimán. The natural gas reservoir formed in the Upper Pannonian sandstone (Újfalu Formation) was discovered by the Ki–5 well in 1952. The gas was accumulated in a stratigraphic/lithologic trap in the Neogene pseudoanticline formed above a Triassic basement high block (VÖLGYI et al. 1985). The GWC is at 780 m bsl. The combustible part of the gas is 61.2%, the calorific value is 21.5 MJ/m^3, CH_4 59%, CO_2 0.1%, N_2 38.7%.

Liszó. The natural gas field was discovered by the Liszó–1 well in 1976. One reservoir in Middle Triassic limestone and dolomite and nine reservoirs in Lower Pannonian sandstones were located. Reservoirs were formed in combined structural/ stratigraphic trap in the top zone of a basement high, and in the anticline structure above the basement high, in lithologic traps (VÖLGYI et al. 1985, TORMÁSSYNÉ et al. 2002b).

— *Nr. 1 (Mz) Triassic basement reservoir:* the GWC in the high carbon dioxide content free gas reservoir is at 2,320 m bsl, the combustible part of the gas is 24.6%, the calorific value is 9 MJ/m^3, CH_4 23.6%, CO_2 69.7%, N_2 6.7%,C_{5+} 1.33 g/m^3. The density of the paraffinic type condensate is 773.3 kg/m^3.

— *Lower Pannonian nr. 2–9 reservoirs:* the GWC in the nine free gas reservoirs is at 1,615–1,292 m bsl, the combustible part of the gas is 67.8–86.6%, the calorific value is 25.5–36.9 MJ/m^3, CH_4 63.5–76.9%, CO_2 < 2.6%, N_2 13.4–30.4%, C_{5+} 7.3–80.5 g/m^3 range. The density of the paraffinic condensate is 732 kg/m^3.

Lovászi. The crude oil and natural gas field was discovered by the Lovászi L–1 exploration well in 1940. Hydrocarbons were accumulated in structural/lithologic traps formed in a Neogene anticline. Free gas reservoir in Middle Miocene sandstone, oil reservoirs with gas cap in Lower Pannonian turbidite sandstones (SzolnokSandstone Fm.) (Lovászi, Sziget, Lower Rátka, Upper Rátka, and Páka reservoir horizons) and a free gas reservoir in Lower Pannonian sandstone (Szintfeletti horizon) were located in that field (VÖLGYI et al. 1985).

— *"Torton"reservoir horizon:* the GWC in the Badenian/Sarmatian free gas reservoir is at 1,735 m bsl. The combustible part of the gas is 97.9%, the calorific value is 39.7 MJ/m^3, the C_{5+} content is 74 g/m^3 (VÖLGYI et al. 1985).

— *Lovászi reservoir horizon:* the intermediate oil with gas cap was accumulated in the Szolnok Formation. The OWC is 1,311 m bsl, the oil density is 820 kg/m^3. The combustible part of the cap gas is 97%, the calorific value is 47.7 MJ/m^3, C_{5+} content is 80 g/m^3.

— *Sziget reservoir horizon:* the OWC is at 1,145 m bsl, the density of the intermediate type oil is 820 kg/m^3. The combustible part of the cap gas is 97%, the calorific value is 41.8 MJ/m^3, the C_{5+} content is103 g/m^3.

— *Upper Rátka reservoir horizon:* the OWC is at 1,080 m bsl, the density of intermediate oil is 820 kg/m^3. The combustible part of the gas cap is 97%, the calorific value is 43.3 MJ/m^3, the C_{5+} content is 120 g/m^3.

— *Lower Rátka reservoir horizon:* the OWC is 1,080 m bsl, the density of intermediate oil is 820 kg/m^3. The combustible part of the cap gas is 97%, the calorific value is 43.3 MJ/m^3, the C_{5+} content 130 g/m^3.

— *Páka reservoir horizon:* Thirteen small reservoirs are located here (VÖLGYI et al. 1985). The consolidated value of the OWC is at 1,070 m bbsl, the density of intermediate oil is 800 kg/m^3. The combustible part of the cap gas is 93.6%, the calorific value is 41.9 MJ/m^3, the C_{5+} content is 60 g/m^3.

— *Szintfeletti reservoir horizon:* free gas reservoir, the GWC in the reservoir found in Lower Pannonian sandstone is at 970 m bsl, the combustible part of the gas is 97.6%, the calorific value is 41 MJ/m^3, the C_{5+} content is 60 g/m^3. Based on the data from VÖLGYI et al. (1985), the methane content is 85.6%, CO_2 1.6%.

Mezőcsokonya. Reservoirs of the natural gas field explored by the Mcs–1 well in 1964 are accumulated in the Middle Miocene Badenian Lajta Limestone Formation and in the Lower Pannonian Szolnok Sandstone Formation. The natural gas field is characterised by stratigraphic/lithologic traps formed in the pseudoanticline above a volcanic body (VÖLGYI et al. 1985). The carbon dioxide gas occurrence here was discovered in 1966 (JUHÁSZ, KUMMER ed. 1997).

— *Mezőcsokonya III/B, VI/A2, VI/A1, VI/F, VII reservoirs:* the reservoir content is free gas. The GWC is at 1,636.5–1,468 m bsl, the combustible part of the gas 72.6–88.97%, the calorific value is 26.5–33.6 MJ/m^3, CH_4 71.6–85.7%, CO_2 0.6–6.3%, N_2 9.9–22.1%. Based on the data from VÖLGYI et al. (1985), the nature of the condensate is paraffinic, its density is 740–790 kg/m^3.

— *Mezőcsokonya III/A, IV/B and V/B reservoirs:* the GWC in the carbon dioxide gas reservoirs is at 1,612–1,575 m bsl, the calorific value is 1.5–2.7 MJ/m^3. Based on VÖLGYI et al. (1985) the combustible part is between 7.1 and 4.5%.

— *Mezőcsokonya I, II, IV/A and V/A reservoirs:* the GWC in the Middle Miocene free gas reservoirs is at 1,577.5–1,560 m bsl, the combustible part of the gas is 27.2–52.3%, the calorific value is 8.8–22.8 MJ/m^3, CH_4 25–50.7%, CO_2 31.6–67.1%, N_2 5.8–17.3%. Based on VÖLGYI et al. (1985) the condensate is of paraffinic type, its density is 770 kg/m^3.

Mezőcsokonya West (Mezőcsokonya-Nyugat). The oil occurrence was discovered by the Mcs-Ny–2 well. The multiple reservoir was formed by stratigraphic/lithologic trapping and is found in the pinching-out Sarmatian limestone on the north-western limb of a Miocene structure and in the underlying volcanics (Mátra Volcanic Formation Group). The OWC in the reservoir is 1,810 m bsl, the density of the intermediate oil is 890 kg/m^3. The sulphur content of the oil is 1%. The dissolved gas content is 28 m^3/ m^3, the combustible part of the gas 90.9%, the calorific value is 50.6 MJ/m^3, CH_4 65.4%, CO_2 2.5%, N_2 6.6%. The C_{5+} content is high: 192.9 g/m^3.

Nagyatád. The oil reservoir is found in sedimentary–volcanic beds, in Middle Miocene Karpatian–Badenian sandstone, tuffitic sandstone, siltstone and fractured shaly marl (GYARMATI 2008). The oil reservoir has no gas cap, and only oil influx subject to swabbing was found. The longitudinal axis of the approximately 6 km long, elliptical oil reservoir structure is NNW–SSE. The oil of the reservoir discovered by the Nagy–1, –2 and –3 wells is of a moderately matured nature. Paraffinic type oil is known from the Nagy–1 and Nagy–3 wells, and oil of intermediate type was found in the Nagy–2 well (GYARMATI 2008). The oil density is 861 kg/m^3. The combustible part of the gas is 96.1%, the calorific value is 72.6 MJ/m^3, CH_4 41.4%, CO_2 2.9%, N_2 1.0%.

Nagybakónak. The Nab–1 well was drilled in 1976 discovered undersaturated oil reservoirs in the upper, fractured, weathered, brecciated section of Triassic basement rocks and in the Middle Miocene Badenian basal conglomerate. Further exploration was launched in 1983–84, where the Nab-É–1 well also hit the oil reservoir in Triassic formations (JUHÁSZ, KUMMER ed. 1997).

— *Nab1Mz reservoir:* the OWC in the multiple reservoir is at 2,316 m bsl. The density of the paraffinic oil is 859 kg/m^3. The dissolved gas content is 20 m^3/m^3, the combustible part of the gas 4.7%, the calorific value is 1.7 MJ/m^3, CH_4 4.5%, CO_2 94.9%, N_2 0.5%.

— *NabM2 reservoir:* the Nab–I well (1994–95) discovered oil and natural gas in Badenian conglomerate overlying Triassic basement rocks (JUHÁSZ, KUMMER ed. 1997). The density of the intermediate oil is 855 kg/m^3. The combustible part of the dissolved gas is 93%, the calorific value is 55.5 MJ/m^3, CH_4 57.7%, CO_2 5.6%, N_2 1.2%.

Nagylengyel–Barabásszeg–Szilvágy–Szilvágy South. Seventeen reservoirs are recorded in the field group created by the concentration of the former Nagylengyel, Barabásszeg, Szilvágy and Szilvágy South (Szilvágy–Dél) oil fields.

The Nagylengyel oil field was discovered by the Nl–2 well in 1951. Four reservoirs in Upper Triassic Main Dolomite, eight reservoirs in Upper Cretaceous rudist limestone (Ugod Limestone Fm), one reservoir in Upper Cretaceous gryphaea marl (Jákó Marl Formation) and one reservoir in Middle Miocene Badenian glauconitic green sandstone (Tekeres Schlier Formation) were located in the field (VÖLGYI et al. 1985).

— *Upper Triassic reservoirs:* situated in the I–IV, V–VI, VII, XIV blocks in Main Dolomite. The OWC in the reservoirs is between 2,510–1,970 m bsl, the density of the paraffinic-intermediate type oil is 920–970 kg/m^3.

— *"Rudist" succession reservoirs*: the reservoir rock in the I–IV, V–VI, VII, VIII, X.É, X.D, XI, XIV blocks is the Upper Cretaceous Ugod Limestone Formation. The OWC is at 2,340–2,010 m bsl, the density of the paraffinic-intermediate oil is 930–990 kg/m^3. The sulphur content of the oil is 1.9–5.1%.

— *"Gryphaea" succession reservoir:* one oil reservoir is found in the limestone intercalation of the Upper Cretaceous gryphaea marl (Jákó Marl Fm), in Blocks I–IV. The OWC is at 2,100 m bsl, the density of the paraffinic-intermediate nature oil is 950 kg/m^3. The sulphur content of the oil is 3.3%.

— *"Glauconitic" succession reservoir:* One reservoir in Blocks I–IV formed in the glauconitic sandstone of the Middle Miocene Badenian Tekeres Schlier Formation. The OWC is at 1,690 m bsl, the density of paraffinic oil is 970 kg/m^3. The sulphur content of the oil is 4%.

— *Barabásszeg oil reservoir*. This was formed in Upper Triassic dolomite (Main Dolomite Formation), Upper Cretaceous limestone (Ugod Limestone Formation) and Middle Miocene Badenian lithothamnium limestone (Lajta Limestone Fm) sequence, and was explored by the Ba–3 well in 1958. The reservoir is found in the Nagylengyel IX block. The OWC is at 2,055 m bsl, the density of the paraffinic-intermediate type oil is 939 kg/m^3, the sulphur content is 1.2%.

Szilvágy oil reservoir. This was discovered by the Szil–13 well in 1968. The reservoir was formed in a stratigraphic trap along the Triassic–Cretaceous (Main Dolomite, Ugod Limestone Fm) unconformity (MOLNÁR et al. 1998b, VÖLGYI et al. 1985). The OWC is at 2,470 m bsl, the density of the paraffinic-intermediate type oil is 920 kg/m^3, the sulphur content of the oil is 1.22%.

— *Szilvágy South (Szilvágy-Dél) oil reservoir*. Discovery wells are the Szil–31 (1970) and the Szil–33 (1970). The reservoir was formed above the top Jurassic unconformity surface and is found in a lithologic, pinched-out trap in the Upper Cretaceous basal conglomerate and rudist limestone beds (Ugod Limestone) (VÖLGYI et al. 1985, SZABÓ-HORTI et al. 2012). The oil is of the naphthenic type, its density is 850 kg/m^3.

Ortaháza. The oil and gas field was discovered by the Or–2 well in 1970. A number of reservoirs were formed in Lower Pannonian sandstone (Szolnok Fm). Four horizons are distinguished from the bottom to the top in those beds: the Kissziget, Eperje, Gutorfölde and Ederics horizons (VÖLGYI et al. 1985). The Kissziget horizon contains free gas reservoirs and an oil reservoir with gas cap, the Eperje horizon contains free gas reservoirs and oil reservoirs with dissolved gas or gas cap, the Gutorfölde horizon contains oil reservoir with gas cap and free gas reservoirs, the Ederics horizon contains free gas reservoirs, dissolved gas containing oil reservoir and oil reservoir with gas cap.

– *Ortaháza–1 oil reservoir with gas cap:* the reservoir rock of the multiple reservoir is Upper Triassic limestone (Dachstein Fm) and Miocene limestone-calcareous sandstone (Lajta Limestone Fm). The OWC is at 1,856 m bsl, the density of the paraffinic oil is 850 kg/m^3, the sulphur content is 0.3%. The combustible part of the cap gas is 83.2%, the calorific value is 32.1 MJ/m^3, CH_4 76.2%, CO_2 8.8%, N_2 8%. The C_{5+} contents 30.4 g/m^3. The dissolved gas content is 37 m^3/m^3, the combustible part of the gas 75.9, the calorific value is 30.7 MJ/m^3.

— The GWC in the *Lower Pannonian free gas reservoirs* is in 1,585–1,394.5 m bsl, the combustible part of the gas is 88.9–95.8%, the calorific value is 35.7–48.1 MJ/m^3. CH_4 84.8–91.5%, CO_2 0.8–4.4%, N_2 1–7.5%. The C_{5+} content is 13.5–26.77 g/m^3. The density of the intermediate type condensate is 739–750 kg/m^3 (VÖLGYI et al. 1985).

— The OWC in the *Lower Pannonian oil reservoirs with gas cap* is between 1,583–1,396 m bsl. The density of the intermediate oil varies between 800 and 870 kg/m^3. The combustible part of the cap gas is 93.3–95.0%, the calorific value is 36.5–37.3 MJ/m^3, CH_4 86.8–89.6%, CO_2 0.7–2.5%, N_2 1.1–6.0%.

— The OWC in the *Lower Pannonian undersaturated oil reservoirs* is between 1,402–1,558 m bsl, the density of the intermediate oil is 820–850 kg/m^3. The dissolved gas content is less than 58 m^3/m^3, the combustible part of the gas is 91.4–93.9%, the calorific value is 36.7–41.9 MJ/m^3, CH_4 77.9–88.3%, CO_2 0.8–2.5%, N_2 3.8–7.5%. The highest C_{5+} content is 34.7 g/m^3.

Ortaháza East. The hydrocarbon field was discovered by the Or-K–2 well in 1985. The field consists of an undersaturated oil and four dry gas reservoirs. The oil reservoir was formed in Upper Triassic limestone (Dachstein Limestone Fm), while the gas reservoirs in Lower Pannonian sandstone, silty sandstone (Szolnok Sandstone Fm).

— *Triassic reservoir:* the OWC in the oil reservoir of the Upper Triassic fractured Dachstein Limestone is at 1,650 m bsl. The density of the paraffinic-intermediate type oil is 870 kg/m^3. The calorific value of the dissolved gas is low (15.1 MJ/m^3), as the combustible gas content is 36.7%, CO_2 55.2%, N_2 8.1%.

— *Lower Pannonian free gas reservoirs* (from bottom to top: Csömödér–1, Eperje 1f, Gutorfölde–1): single reservoirs are situated in delta sandstones (Jósvai 2001b). The GWC in the reservoirs is between 1,425–1,341.5 m bsl. In the Gutorfölde–1 reservoir the combustible gas content is 94.4%, the calorific value: 36.1 MJ/m^3, CH_4 89.8%, CO_2 1.1%, N_2 4.5%, C_{5+} content: 56.1 g/m^3.

Őriszentpéter South (Őriszentpéter-Dél). Some 30 gas containing reservoir were found in the natural gas field which was discovered by the Őri-D–1 well in 1989. The gas accumulated in the sandstone layers of the Middle Miocene upper Badenian shaly marl and sandstone sequence (Szilágy Shaly Marl Fm), while the youngest reservoir is situated in Sarmatian beds (Kozárd Fm) (Tormássyné et al. 1992). The combustible part of the gas is 97.9%, the calorific value is 38 MJ/m^3, CH_4 86.5%, CO_2 1.7%, N_2 0.4%, C_{5+} 0.3 g/m^3.

Geophysical well logs of the Viszák–1 well drilled in the Őrség-deep zone area are shown on Figure 4.2.9 as a sample for the region.

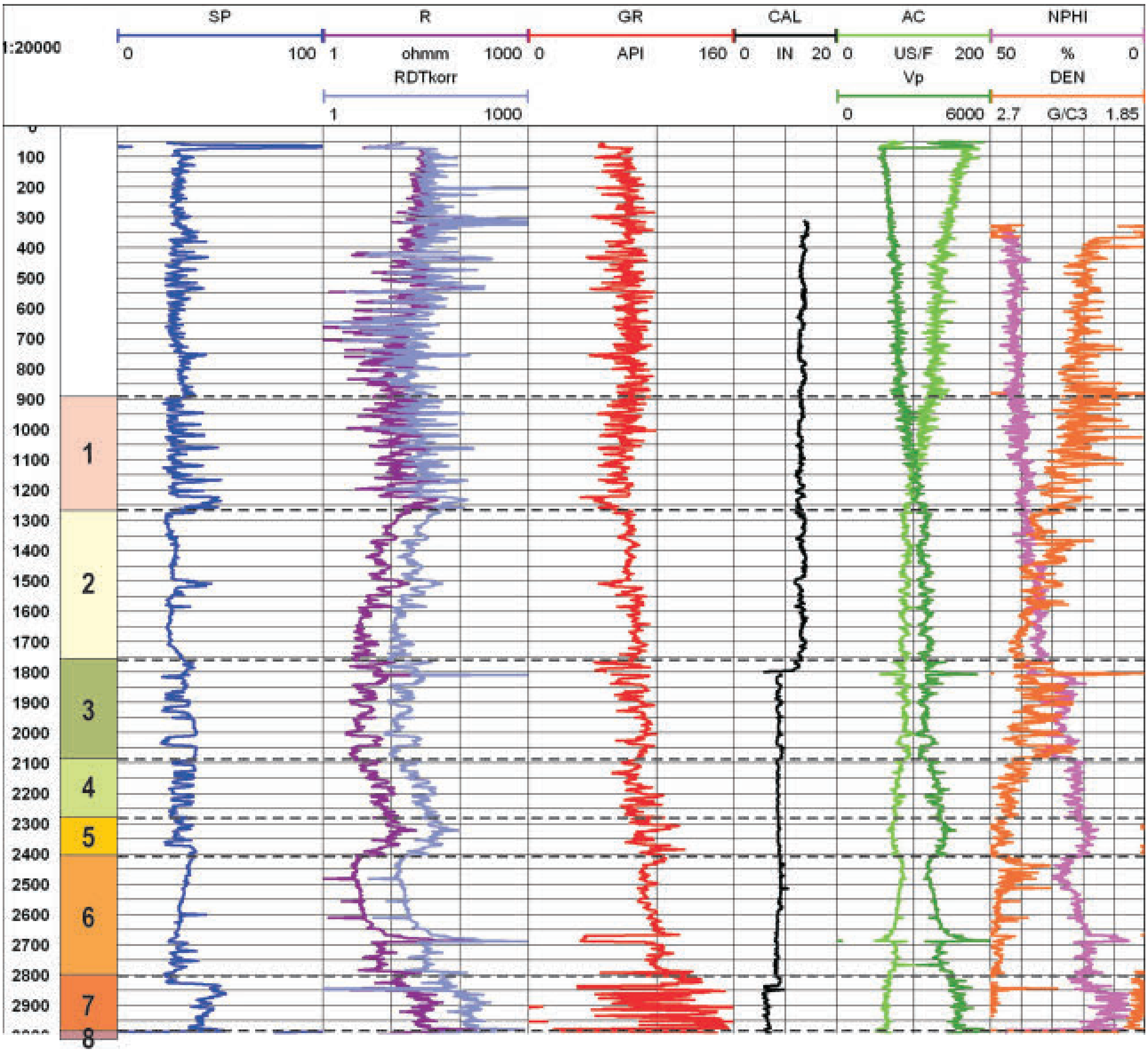


Figure 4.2.9. Geophysical well logs of the Viszák Visz–1 well

Legend: SP: spontaneous potential, R,RDT: electrical resistance; GR: natural gamma-ray; CAL: caliper log; AC: acoustic; Vp: acoustic velocity; DEN: density; NPHI: neutron-porosity log. *Geological stratigraphic column:* 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Szolnok Fm (Lower Pannonian), 4. Endrőd Fm (Lower Pannonian). 5. Miocene, Sarmatian, 6. Miocene, Badenian, 7. Miocene, Karpatian, 8. Cretaceous limestone

Őrtilos. The hydrocarbon occurrence was found by the Őrtilos–1 exploration well in the sandstone layers embedded into marls in the top zone of the Middle Miocene beds (*ŐrtiM–I–IV reservoirs*). The OWC in the undersaturated oil reservoirs is between 2,152–2,112 m bsl. The density of the intermediate oil is 718–818 kg/m^3. The dissolved gas content is 276–313 m^3/m^3, the combustible part of the gas is 96.6–96.7%, the calorific value is 43.7–45.3 MJ/m^3, CH_4 80.0–81.8%, CO_2 1.7–1.9%, N_2 0.5–0.7%. The C_{5+} content of the gas of ŐrtiM–III reservoir is 105.4 g/m^3.

Pat. Although Pat–1–4 wells drilled in the 1960s proved dry, hydrocarbon traces were detected in them. An *oil reservoir* was explored by the Pat–5 well (1989). The oil was accumulated in the calcareous marl member of Lower Pannonian Endrőd Marl Formation (GYARMATI 2008). The OWC is 2,015 m bsl, the oil is of intermediate type, the density of that is 872.4 kg/m^3.

The Pat–7 well (1989) discovered a *mixed gas reservoir* in the higher parts of the Triassic dolomite, the influx consisted mainly from carbon dioxide (JUHÁSZ, KUMMER ed. 1997). The GWC is at 1,742.5 m bsl, the combustible part of the gas is 19.9%, calorific value: 7.3 MJ/m^3, CH_4 19.6%, CO_2 72.2%, N_2 7.9%. In the Pat–7 well oil traces were also discovered from the Lower Pannonian sandstone (GYARMATI 2008).

Pátró. Almost pure CO_2 gas was discovered in Triassic formations by the Pátró–1 well in 1976, and a free gas reservoir was found containing more methane than was found before in Lower Pannonian sandstone (KŐRÖSSY 1989).

— *Pátró–I. Triassic reservoir:* the reservoir is formed in a succession of dolomitic limestone, dolomite, quartzite, siliceous sandstone, slaty marl, shale and polymict breccia. The GWC is at 1,826 m bsl.

— *Pátró–I. Pl2 reservoir:* this was formed in Pannonian sandstone. Mixed gas (CO_2 rich combustible gas) (TORMÁSSYNÉ et al. 2002a, b; BERNÁTHNÉ 1997b). The GWC in the reservoir is at 1,291 m bsl.

Pusztaapáti. The oil-occurrence was discovered by the Pusz–1 well in 1973. The oil accumulated in a subconformity

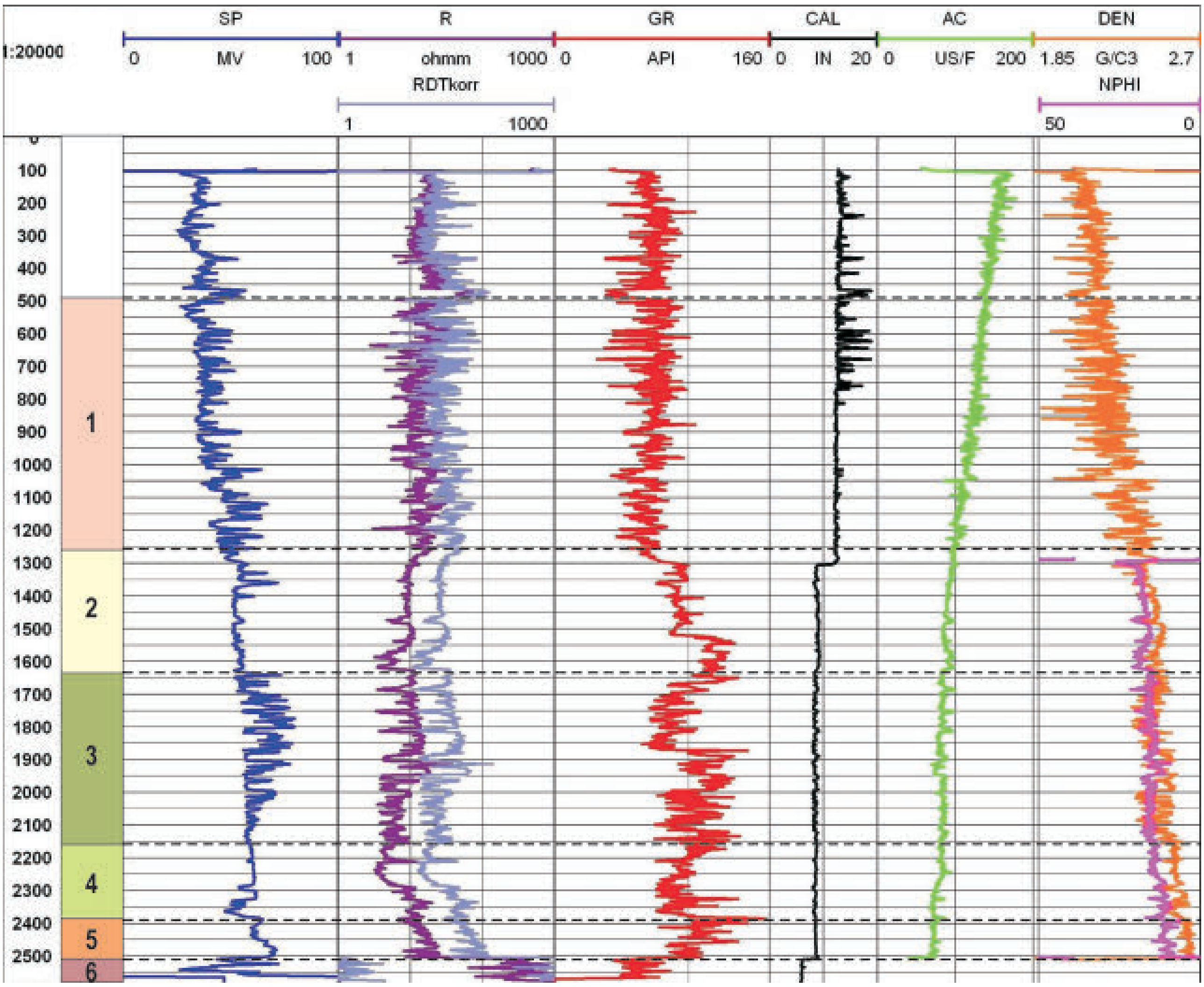


Figure 4.2.10. Geophysical well logs of the Kustánszeg Kus-1 well

Legend: SP: spontaneous potential; R,RDT: electrical resistance; GR: natural gamma-ray; CAL: caliper log; AC: acoustic; DEN: density; NPHI: neutron- porosity profile. *Geological column:* 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Szolnok Fm (Lower Pannonian), 4. Endrőd Fm (Lower Pannonian), 5. Middle Miocene formations, 6. Triassic dolomite

trap formed below the Triassic–Miocene unconformity. The reservoir rock is Upper Triassic Main Dolomite (Völgyi et al. 1985). Paraffinic type oil was accumulated, the OWC is at 2,530 m bsl, the density of oil is 920 kg/m^3.

Geophysical well logs of the Kustánszeg–1 well drilled in the neighbourhood of Pusztaapáti are shown on Figure 4.2.10.

Pusztamagyaród. The natural gas occurrence was located in 1972 by the Pu–3 well. The stratigraphic trap was formed in a Neogene pseudoanticline structure above the pre-Cenozoic basin basement. The accumulated gas is situated in the top of the Badenian lithothamnium limestone (Lajta Limestone Formation) under Lower Pannonian shaly marl seal (Völgyi et al. 1985, Kőrössy 1988).

— *Pu–3,5M reservoir:* the GWC is at 1,520 m bsl. In the free gas reservoir discovered by the Pu–3 and Pu–5 wells in Middle Miocene (Badenian) rocks. The combustible part of the gas is 75.6%, the calorific value is 31.2 MJ/m^3, CH_4 68%, CO_2 0.5%, N_2 23.9%, the C_{5+} content is 105.2 g/m^3.

— *Pu6M reservoir:* the Middle Miocene free gas reservoir was discovered by the Pu–6 well. The GWC here is also at 1520 m bsl. The combustible part of the gas 92.6%, the calorific value is 38.3 MJ/m^3, CH_4 83.5%, CO_2 0.5%, N_2 7.41%.

Pusztaszentlászló (Hahót–Söjtör). The oil occurrence was discovered by the H–5 well in 1941. The reservoir of the undersaturated oil is Triassic dolomitic limestone and dolomite together with the overlying Badenian lithothamnium limestone (Lajta Limestone Fm). The multiple reservoir is situated in a stratigraphic trap on the top of the tectonically and morphologically formed Neogene basement structure, along the Triassic/Miocene unconformity surface (Völgyi et al. 1985). The OWC depth in the reservoir is at 1,290 m bsl, the density of intermediate oil is 870 kg/m^3. The sulphur content of the oil is 1%, the dissolved gas content: 30 m^3/m^3, combustible part of the gas 95%, calorific value 18 MJ/m^3.

Pusztaszentlászló East (Pusztaszentlászló-Kelet). The oil field was located by the Pszl.K–1 well (1990).

— *PszlK–1 reservoir:* the undersaturated oil reservoir was formed in fractured Triassic limestone. The OWC is at 1,100 m bsl, the density of the intermediate oil density is 842.4 kg/m^3. The dissolved gas content is 8 m^3/m^3, the calorific value of the gas is 21.6 MJ/m^3.

— *PszlK–4 reservoir*: the Pszl.K–4 well was drilled in 1991 and discovered a very small oil reservoir in lithological trap. The OWC in the Lower Pannonian sandstone reservoir is at 970.5 m bsl, the density of intermediate oil is 854.5 kg/m^3, the sulphur content is 0.3% (Juhász, Kummer ed. 1997).

Rádiháza. The Rádiháza–1 well (2011) drilled in the Bak–Nova trough discovered six gas reservoirs in stratigraphic traps in Lower Pannonian turbidite succession. The reservoir rocks are composed of turbidite silt and sandstone with shaly marl strips of channel, rived bed and point bar facies. The main reservoir deposited at an average depth of 1,510 m. The combustible part of the gas is 90.7%, N_2 8.5%, practically without any carbon dioxide and hydrogen sulphide. Its calorific value is 34.5 MJ/m^3; the gas condensate has a density of 721 kg/m^3 (Németh et al. 2013a).

Sávoly South (Sávoly-Dél). The oil field was discovered by the Sáv.D–1 well in 1997. Two undersaturated oil reservoirs were located. The multiple reservoirs developed in Mesozoic carbonate formations (partly in Carnian limestone) and Neogene clastics made up of weathered volcanics (Molnár et al. 1999a). The OWC in the reservoirs is at 1,960 m, the oil is of intermediate type. The density is 890–920 kg/m^3. The dissolved gas content is 30 m^3/m^3, the combustible part of the gas is 73.1–82.1%, the calorific value is 32.2–35.2 MJ/m^3, CH_4 55.8–76.7%, CO_2 16.3–24.9%, N_2 1.6–2%.

Sávoly South-east (Sávoly-Délkelet). The oil field was discovered by the Sáv.DK–1 well in 1995. The reservoir was situated in the uppermost zone of a Triassic carbonate (Igal Fm) succession (Kovács A. et al. 1998). Other undersaturated oil reservoirs were discovered later in Middle Miocene Badenian lithothamnium limestone – limestone breccia – calcareous sandstone succession (Lajta Fm) by the wells Sáv.DK–1, –4, –9, Szőcsénypuszta Szőcs–1 (1998), Kápolnapuszta Káp–1, Káp–3 (1999) and Káp–4 (2006). All together, eight oil reservoirs are known in this field.

The depth of the OWC in the *Triassic reservoi*r is 1,917 m, the density of the intermediate type oil is 920 kg/m^3, sulphur content: 2.9%, dissolved gas content: 50 m^3/m^3. The combustible part of the gas is 29.9%, the calorific value is 14.2 MJ/m^3, CH_4 24.9%, CO_2 65.1%, N_2 5.4%, C_{5+} 35.3 g/m^3.

The density of the intermediate oil in the seven *Badenian reservoirs* is between 910–927 kg/m^3. The dissolved gas content is 11.5–29.0 m^3/m^3.

Sávoly East (Sávoly-Kelet). The Sáv.K–2 well discovered hydrocarbon accumulations in two horizons, which are mixed gas accumulations consisting of predominantly CO_2 in Lower Pannonian sandstone lens and Middle Miocene andesite and sandstone (Molnár et al. 1999a).

— The GWC in the *Middle Miocene free gas reservoir* is at 1,280 m bsl, the combustible part of the gas 27.2%, the calorific value is 8.6 MJ/m^3, CH_4 22.5%, CO_2 72.8%, N_2 4%. The C_{5+} content is 1.5 g/m^3.

— The GWC in the *Lower Pannonian reservoirs* is at 1,270–1,033.5 m bsl, the combustible part of the gas is 54.7–81.4%, the calorific value is 20.2–30.1 MJ/m^3, CH_4 53.2–79.7%, CO_2 2.9–36.3%, N_2 9–15.7%, C_{5+} content 4.5–79.7 g/m^3.

Sávoly West (Sávoly-Nyugat). There are two reservoirs registered in the field.

— The *oil reservoir with gas cap of Sáv.Ny–1 well* (1992) was found in the top layers Upper Triassic dolomite, dolomite breccia, limestone (Igal Formation), in structural trap. The OWC is at 1,650 m bsl, the density of the intermediate oil is 939 kg/m^3, the sulphur content of the oil is 0.89%. The dissolved gas content is 67 m^3/m^3, the combustible part of the gas is 17.6%, the calorific value is 7 MJ/m^3, CH_4 7.54%, CO_2 80.25%, N_2 2.1%.

— The *free gas reservoir of Sáv.Ny–2 well* (1993) was formed in Lower Pannonian sandstone. The GWC is at 1,397.5 m bsl, the combustible part of the gas is 96%, the calorific value is 38 MJ/m³, CH_4 91.8%, CO_2 0.8%, N_2 2.7%. The condensate content is 37.3 g/m³.

Somogysámson. The reservoir rocks of the oil and gas occurrence are Middle Miocene Badenian sandstone, marl, lithothamnium limestone (Lajta Limestone Fm) and Karpatian andesite tuff beds (Mátra Vulcanite Formation Group, Tar Dacite Tuff Fm).

— *Som2M2b reservoir*: The Som–2 well (1983) explored an undersaturated oil reservoir had formed in the Middle Miocene reservoirs. The OWC is at 1,575.5 m bsl, the density of intermediate oil is 904 kg/m³. The dissolved gas content is 24.1 m³/m³, the combustible part of the gas is 96.4%, the calorific value is 55.8 MJ/m³, CH_4 72.4%, the carbon dioxide content is negligible, N_2 3.4%. The condensate content is 385.4 g/m³.

In the Somogysámson area the Som–3 well drilled a gas reservoir in 1983–84 in Karpatian volcanics and Badenian rocks (see Horvátkút) (GYARMATI 2008).

Somogyudvarhely. A free gas reservoir was discovered by the So–3 well in 1978. The gas accumulated in the fractured Palaeozoic metamorphic rocks. Poor quality CO_2 rich gas occurred in the well in commercial quantities, accompanied by oil traces (KŐRÖSSY 1989). The combustible part of the gas is 17.8%, the calorific value is 6.4 MJ/m³. The origin of CO_2 gas in several wells in the area — such as the So–3 well — can be associated with the repeatedly occurring volcanic activity in the Middle Miocene (BERNÁTHNÉ 1997d).

Szentgyörgyvölgy. The Szen–I well (1989) provided poor quality gas from the Cretaceous rudist limestone (Ugod Limestone Fm), and the unconformably overlying Karpatian beds (Ligeterdő Formation) (JUHÁSZ, KUMMER ed. 1997). The Kógyár–1 well was drilled by the Hungarian Horizon Energy Ltd in 2001. A small sized gas reservoir was discovered also in Cretaceous Ugod Limestone. The OWC in the reservoir is at 3,189 m bsl, the calorific value is 14.9 MJ/m³, the C_{5+} content is 1.4 g/m³.

Tarany. Two undersaturated oil reservoir were discovered by the Tar–1 well in 1961. The oil accumulated in stratigraphic/lithologic traps developed in Middle Miocene formations. The reservoir rock is Karpatian gravelly sandstone (Budafa Formation), and Badenian lithothamnium limestone – calcareous sandstone/sandstone (Lajta Limestone Fm). The density of the intermediate type oil is 808 kg/m³. The combustible part of the dissolved gas is 88.9%, the calorific value is 43.4 MJ/m³, CH_4 65.3%, CO_2 5.2%, N_2 5.9%, C_{5+} 0.97 g/m³ (VÖLGYI et al. 1985).

Tatárvár. The HHE. Tatárvár–1 well, drilled by Hungarian Horizon Energy Ltd in the neighbourhood of Buzsák in 2008, discovered undersaturated oil reservoir in Badenian lithothamnium limestone reservoir. The well was laid on a buried Middle Miocene carbonate bar situated in a positive flower structure of a wrench fault zone. Little oil can be produced from the reservoir because of the porous limestone structure, with more and more water being produced along with the oil. The HHE. Tatárvár–2 well, drilled in 2008–2009, also hit the oil-containing Badenian limestone; but it produced only for a couple of months due to high water content. The HHE. Tatárvár–3 well (2009) explored an uncommercial oil accumulation and the well was abandoned. The density of the naphthenic type oil is 980 kg/m³, the sulphur content is relatively high, the dissolved gas content very low (KERESZTES et al. 2014).

Tófej. The Tófej–1 well was drilled in 2011, and proved to be productive; it was completed to produce natural gas. The stratigraphic trap was formed in the Lower Pannonian Upper Nova horizon. The reservoir rock is turbidite sandstone of the upper zone of the Szolnok Formation. The combustible part of the gas is 91.2%, the calorific value is 34.6 MJ/m³, CH_4 85.2%, CO_2 0.7%, N_2 8.1%. The density of the paraffinic type condensate is 727 kg/m³ (SZENTGYÖRGYINÉ et al. 2013).

Törökkoppány. The free gas occurrence was discovered by the Törökkoppány Tk–1 well drilled in 2001. The Törökkoppány structure is an anticline bordered by faults; its evolution is assumed to be associated with Early Pannonian tectonic movements. The reservoir was formed in Middle Miocene Badenian limestone. The cap rock is formed by Lower Pannonian formations (BURNS et al. 2002). The GWC is at 530 m bsl. The combustible part of the gas is 94.4%, the calorific value is 31.4 MJ/m³, CH_4 91.8%, CO_2 0.1%, N_2 7.8%.

Újfalu. The oil and natural gas field was located by the Újfalu Ú–1 well in 1940. The U–I well drilled in 1978 explored the underlying strata of the Neogene sedimentary sequence as well. The reservoir rock is Lower Pannonian sandstone; hydrocarbons were accumulated in lithologic and structural combined traps in a folded Neogene dome (VÖLGYI et al. 1985).

— *Újfalu Lower horizon, Újfalu Lower–1, –2 reservoirs*: the OWC in the undersaturated oil reservoirs is at 1,333 m bsl, the density of the paraffinic-intermediate type oil is 870 kg/m³. The combustible part of the dissolved gas is 97.5%, the calorific value is 36.8 MJ/m³, the C_{5+} content is 6 g/m³.

— *Újfalu Lower Pannonian free gas reservoirs*. The GWC is at 1,070 m bsl, the combustible part of the gas is 95.3%, the calorific value is 37.3 MJ/m³, CH_4 88.5%, CO_2 1.44%, N_2 4.3%.

Vétyem. The gas field was discovered by the V–1 well in 1947 (VÖLGYI et al. 1985). The reservoir rock is Lower Pannonian sandstone. The Vétyem V–I well (2005) drilled in a later exploration period explored a free gas reservoir in Middle Miocene Lower Badenian glauconitic sandstone.

— *V1Pl1–1611 free gas reservoir*: the GWC is at 1,450 m bsl, the combustible part of the gas is 98.1%, the calorific value is 39.8 MJ/m³. CH_4 88.5%, CO_2 0.4%, N_2 1.5%, C_{5+} 11.9 g/m³.

— *M2gl glauconitic sandstone reservoir*: the GWC is at 2442 m bsl, the combustible part of the gas is 97.7%, the calorific value is 41.8 MJ/m^3, CH_4 83.6%, CO_2 1.9%, N_2 0.4%, C_{5+} 31.6 g/m^3.

Vétyem East (Vétyem-Kelet). The Vétyem-K–1 (1960) and K–2 (1961) wells discovered free gas reservoirs formed in Lower Pannonian sandstone (Szolnok Formation).

— *VK1.5Pl1–1671 reservoir no.1:* the GWC in the is at 1,481 m bsl in the structural trap, the combustible part of the gas is 98.1%, the calorific value is 39.8 MJ/m^3, CH_4 88.5%, CO_2 0.4%, N_2 1.5%, C_{5+} 11.9 g/m^3.

— *Reservoir no. 2:* the GWC is at 1,420 m bsl, the combustible part of the gas 96.7%, the calorific value is 37 MJ/m^3, CH_4 86.2%, CO_2 0.75%, N_2 2.6%, C_{5+} 18 g/m^3.

Vízvár. The oil and gas field was discovered by the Víz–1 well in 1959. Reservoirs can be found in Lower Pannonian sandstone in lithologic traps formed in a Neogene pseudoanticline structure above the Early Palaeozoic basin basement. Paraffinic and paraffinic-intermediate type oil can be found in the field (Völgyi et al. 1985). The density of the four undersaturated oil reservoirs is 850 kg/m^3. The calorific value of the dissolved gas is 29.7–44.8 MJ/m^3. The calorific value of the gas in the 24 free gas reservoirs is between 24.0 and 37.7 MJ/m^3. The natural gas reservoirs of the Vízvár field provided intermediate type condensate as well; the density is 784–788 kg/m^3 (Völgyi et al. 1985).

Vízvár North (Vízvár-Észak). The gas and gas condensate field was discovered by the Víz–I geological exploration well (1980) drilled into the buried basement high situated approximately1,000 metres deeper than the above mentioned Vízvár reservoir. The reservoir rock is Middle Miocene polymict breccia and basal conglomerate. The Víz-É–4, well drilled in 1997–98, explored a commercial gas condensate reservoir in Miocene coarse clastic sequence overlain by the Variscan Babócsa Complex (Gellért et al. 2006). The combustible part of the gas/gas condensate is 36.4%, the calorific value is 16.6 MJ/m^3, CH_4 29.2%, CO_2 60.8%, N_2 2.8%, the C_{5+} content is 70.4 g/m^3.

Vízvár shallow (Vízvár-sekély). One oil and one free gas reservoirs were located in this field. The OWC in the oil reservoir with gas cap is 1,753 m bsl, the density of the paraffinic oil is 848 kg/m^3, the dissolved gas content is 96 m^3/m^3. The combustible part of the gas is 82%, the calorific value is 30.7 MJ/m^3, CH_4 75%, CO_2 15%, N_2 3%. The GWC in the free gas reservoir is at 1,712 m bsl, the combustible part of the gas is 89.2%, the calorific value is 34.7 MJ/m^3, CH_4 9.9%, CO_2 2.8%, N_2 8.0%.

Zalakaros–Sávoly. The oil field was discovered by the Sáv–4 well drilled in 1978–79. The reservoir rock is Lower Triassic dolomite and Middle Triassic limestone. Reservoir fluids were accumulated on the top part of a basement high structure along the Triassic/Neogene unconformity surface, in stratigraphic traps occasionally accompanied by lithologic changes (Völgyi et al. 1985). Two oil reservoirs with gas cap were located here.

– *Zalakaros–Sávoly D–9 reservoir:* the OWC is 1,765 m bsl. The density of intermediate oil is 930 kg/m^3. The combustible part of the cap gas is 20.4%, the calorific value is 8.6 MJ/m^3.

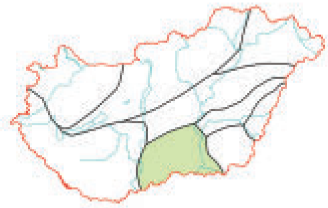
– The *Sávoly reservoir* was discovered by the Sáv–4 well in 1979. The OWC in the oil reservoir with gas cap is 1,665 m bsl. The density of the intermediate type oil is 932 kg/m^3. The carbon dioxide content of the cap is 78.8%, combustible part is 19.1%, the calorific value is 7 MJ/m^3.

Zalakomár. The oil occurrence was discovered by the Zal–1 well (1999). The reservoir was formed in Miocene Badenian lithothamnium limestone–limestone breccia–conglomerate–calcareous marl–marl beds (Lajta Limestone Formation) (Hatalyák et al. 2004). The OWC is at 1,930 m bsl. The density of the intermediate type oil is 900 kg/m^3, the sulphur content of the oil is 1.8%. The dissolved gas content is 34 m^3/m^3, the combustible part of the gas is 97.5%, the calorific value is 53.7 MJ/m^3, CH_4 70.7%, CO_2 1.1%, N_2 1.4%.

Zaláta. The Zaláta–1 exploration well drilled in 2006–2007 discovered commercial quantity natural gas and some condensate near the Croatian–Hungarian state border. The Croatian part of the free gas reservoir was discovered by the Dravica–1 well (2008). The accumulated gas was trapped in Middle Miocene Badenian sandstone and carbonate breccia–conglomerate succession (Gellért et al. 2012). The GWC in the reservoir is at 3,082 m bsl, the combustible part of the gas is 66.8%, the calorific value is 25.6 MJ/m^3, CH_4 63.5%, CO_2 31.4%, N_2 1.8%. The C_{5+} content is 11.3 g/m^3.

Zalatárnok. The natural gas occurrence in the Bak–Nova trough was discovered by the Zt–1 well in 1962. The reservoir accumulated in lithological trap in Lower Pannonian sandstone (in the pinching-out shaly sandstone body belonging to the Tófej Sandstone Member of the Szolnok Sandstone Formation) overlying the fractured Eocene formations (Völgyi et al. 1985, Jósvai 2001). The GWC is at 1,330 m bsl, the free combustible part of the gas is 86.6%, the calorific value is 34.6 MJ/m^3. The C_{5+} content is 15.78 g/m^3.

Hydrocarbon exploration areas in Hungary — Szeged Basin and the Kiskunság



4.3

Edit Babinszki, Zsolt Kovács

Exploration history

In the Danube–Tisza Interfluve the first geophysical surveys and drillings were not carried out for hydrocarbon exploration but instead to explore artesian water reserves. The geological descriptions of the wells are found in the works of Halaváts (1894, 1902). The first oil exploration well was drilled at Baja in 1923 by the Hungarian subsidiary of the Anglo–Persian Oil Co.

Lóczy Jr. (1934, 1941) was the first person to deal with hydrocarbon exploration possibilities in the Szeged Basin. He prepared an expert report for the Hungarian–German Mineral Oil Company (MANÁT) for the purpose of commencing the drilling exploration of the area. Eötvös torsion balance measurements began in 1940, geomagnetic measurements began in 1949, seismic measurements began in 1950, and geoelectric measurements began in the 1960s in areas suitable for hydrocarbon exploration. The activity began with the drilling of MANÁT, and the first well was drilled in Tótkomlós in 1941. The T–1 well blew out, spouting gas and oil (Kőrössy 2005a, b). This well demonstrated the hydrocarbon potential of the southern part of the Great Hungarian Plain area.

In the Kiskunság area a small free-gas reservoir at Tompa was the first occurrence discovered in 1959 and the Rém biogene gas occurrence was the second in 1960. In 1960, by integrating the gas business, the National Oil and Gas Trust (OKGT) was established, which involved the entire Hungarian oil and gas industry. From this period the Great Plain could gradually take over the leading role in oil and natural gas production. During the 1960's the crude oil exploration projects in the Kiskunság region of the Great Plain were shifted towards the Tisza river. In 1962–1963 significant crude oil and natural gas resource was discovered at Üllés, and at Szank in 1964, but progress was hampered by blowouts. This was one of the reasons why the beginning of drilling of Algyő–1 well was delayed, though the geological structure was already identified through seismic acquisition in December 1964. Finally, work could begin in June 1965. At the same time, at the request of an agricultural co-operative, the Water Research Company started to drill a water well (Tápé–1) next to Szeged, at Tápé, more than 4 km from the appointed drilling site of OKGT's oil exploration well. In that Tápé–1 well, unexpectedly, there was a crude oil blow out in July 7, 1965, as the local staff was unprepared for blowout management. Oil exploration experts finally killed the well. Ever since, the Algyő has been the largest hydrocarbon field (with 37.7 million tons recoverable oil and 80.5 Bm^3 recoverable gas) ever in Hungary, as a result of crude oil and natural gas resources discovered with subsequent detailed exploration. Every year from 1965 to 1993, at least one more or less significant occurrence was discovered in the Szeged–Kiskunság area. A number of commercially important discoveries were made since, such as the identification of the Kiskundorozsma, Ferencszállás and Ferencszállás-East, Szeged, Kiszombor, Mórahalom petroleum and natural gas fields in 1965, 1969, 1972, 1973 and 1974, respectively. From the mid-1970s the focus of the drilling operations shifted to the environs of Ásotthalom, Üllés, Ruzsa, and Forráskút. Several minor hydrocarbon occurrences and indications are known in the basin, but have not been put to use. Programmed exploration was suspended in the 1985–95 period, when Mol Hungarian Oil and Gas Plc started explorations again in the Algyő and the Szeged Basin exploration area, completed in 2010.

In the period of exploration up to 2010 two wells were drilled by the Mol Hungarian Oil and Gas Plc in the south-eastern part of the Szeged Basin, on the Algyő basement high ridge, and the wells were qualified as dry. The Szentmihálytelek–1 well drilled on a small basement high structure in 2000 discovered commercial oil reservoirs with good quality dissolved gas.

The Hódmezővásárhely–1 well was drilled in the northern part of the Makó Trough for the exploration of unconventional reservoir formations, and confirmed the presence of tight gas in structure independent position in the Endrőd and Szolnok Formations (Kiss et al. 2010a).

Geological overview

The basement of the area is built up of nappe structures in which the material of the metamorphic basement complex is thrusted over the Palaeo–Mesozoic sequence by the northern, north-western vergence. The area belongs structurally to the Tisza Mega-unit, the north-western half is being part of the Mecsek, the middle part of the Villány–Bihor, and the smaller, south-

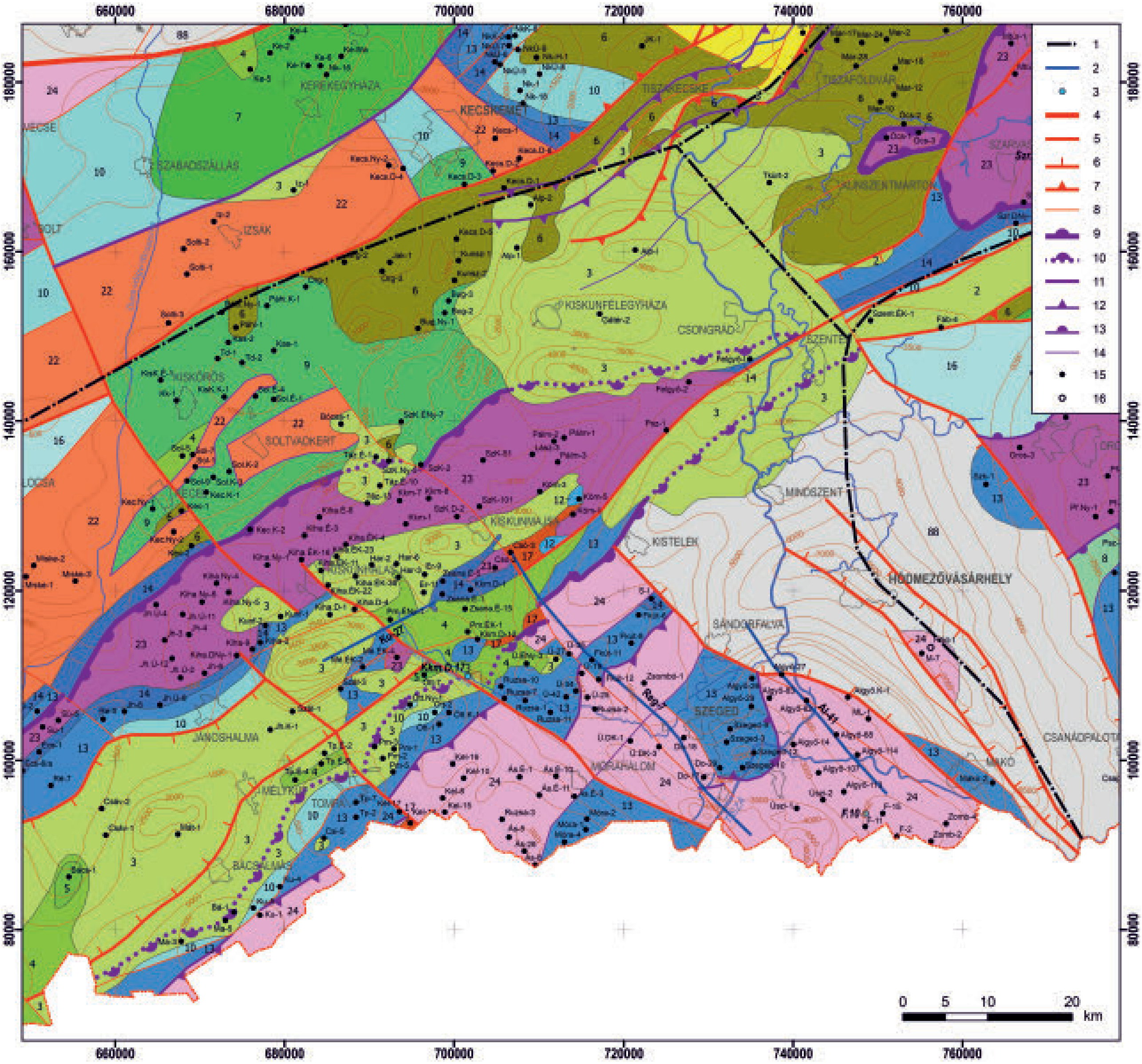


Figure 4.3.1. Pre-Cenozoic geological map of the Kiskunság and the Szeged Basin (HAAS et al. 2010), with the trace lines of the sample seismic sections and the location of wells including sample geophysical logs (figures in this chapter)

Elements of legend: 1. boundary line of the sub-basin, 2. trace line of the sample 2D seismic profile in this chapter, 3. Location of wells including sample geophysical logs on the figures in this chapter, 4. first-order Cenozoic tectonic line, 5. second-order Cenozoic tectonic line, 6.second-order Cenozoic normal fault 7. second-order Cenozoic overthrust, 8. third-order Cenozoic tectonic line, 9. first-order Mesozoic nappe boundary, 10. first-order Mesozoic covered nappe boundary, 11. second-order Mesozoic tectonic line, 12. second-order Mesozoic overthrust, 13. second-order Mesozoic nappe, 14. third-order Mesozoic tectonic line, 15. drillings hit the pre-Cenozoic basement, 16. drillings stopped above the pre-Cenozoic basement

Legend for geological formations: 1. Senonian–Palaeogene pelagic marl, flysch, 2. Senonian flysch, 3. Senonian terrestrial, shallow- and deep-marine (bathyal) formations, 4. Albian marl of basin facies and clastic slope deposits, 5. Lower Cretaceous limestone of platform facies, 6. Lower Cretaceous basic volcanic sand and their redeposited marine sediments, 7. Lower Cretaceous pelagic marl, limestone, 8. Jurassic–Lower Cretaceous pelagic limestone, marl, 9. Middle Jurassic – Lower Cretaceous pelagic limestone, cherty limestone, 10. Lower–Middle Jurassic pelagic fine siliciclastic formation, 12. Upper Triassic – Lower Jurassic coal containing siliciclastic formation, 13. Middle Triassic shallow-marine siliciclastic and carbonate formation, 14. Lower Triassic siliciclastic sediments of fluvial and delta facies, 15. low grade metamorphic Mesozoic formations, 16. Mesozoic formations without subdivision, 17. Permian rhyolite, 22. Variscan granitoid rocks, 23. Variscan metamorphic formation (gneiss, mica, amphibolite), 24. Variscan crystalline rocks without subdivision, 88. inadequately evaluable or unknown basement

eastern area of the Békés–Codru Unit (Figure 4.3.1). The development of the nappe system is the result mainly of the Cretaceous (Austrian) compression tectonics. Within the structural packets of the nappe system of NE–SW direction, perpendicular Cenozoic transverse faults of NW–SE strike can also be observed (HAAS et al. 2010). Considering the latter, the dominant structural element is the normal fault, having a several kilometres extension that separates the area towards the Hódmező-vásárhely–Makó Trough, where the basement sinks down to 7,000 metres below sea level. This trough is to be considered as an asymmetric halfgraben, and it is one of the deepest sedimentary basins in the country. Towards the east no such pronounced structure can be observed, and the basement ascends gradually towards the Battonya–Pusztaföldvár basement high (Figure 4.3.2).

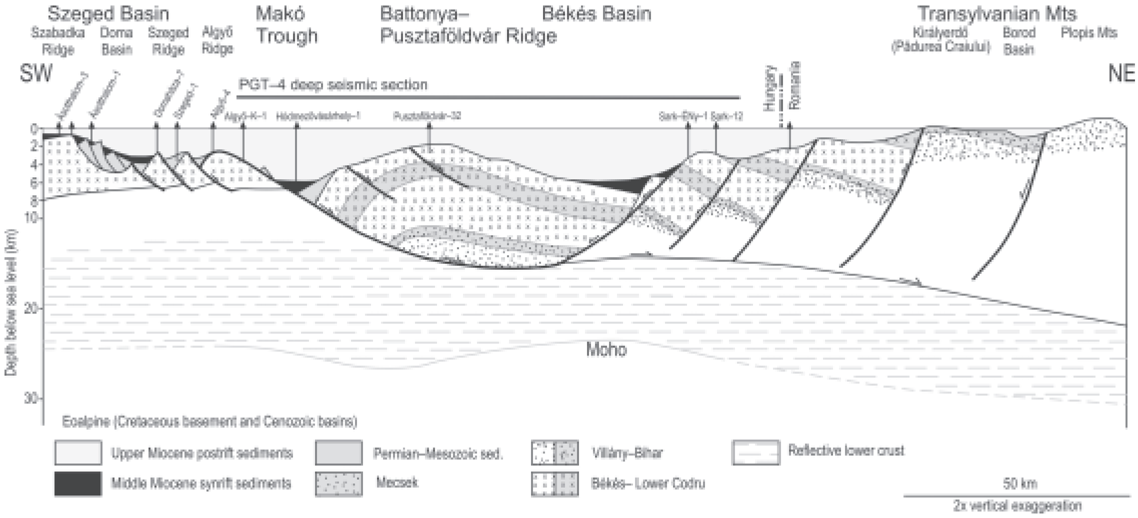


Figure 4.3.2. Regional geological profile in the south-eastern part of the Pannonian Basin (adapted from TARI et al. 1999)

Basement rocks

The basement, which underwent multiple metamorphoses, is basically built up of crystalline formations. The whole area is characterised by the Palaeozoic igneous and metamorphic rocks revealed by the hydrocarbon exploration wells along the Mesozoic nappe boundaries. The older (Triassic), and younger (Jurassic–Cretaceous) basement formations occur more or less parallel with the tectonic boundary.

In the northern part of the area, i.e. in the Mecsek Unit, granitoid and crystalline rocks (migmatite, gneiss, mica) of the Mórágy Complex can be found, which are in a very high position next to the Danube (600 metres below the surface); eastwards, they start descending within a short distance. Near Kecel they are already at around a depth of 2,000 metres. Around Soltvadkert the Mórágy Granite Formation is accompanied by phyllite, which most probably belongs to the Tázlár Phyllite Formation (SZEDERKÉNYI 1998).

In the Villány–Bihor Unit the oldest formation group is made up of Variscan metamorphite succession (gneiss, mica, amphibolite, marble intercalations). The metamorphites and the associated magmatites can be classified into the Körös Complex, in the axial zone of which — as in the case of the Mórágy Complex — a narrow, non-continuous granite range extends, embedded in a continuous migmatite belt.

The metamorphic basement complex of the southernmost part, i.e. the Békés–Codru Unit, consists of Palaeozoic mica and gneiss series (Kelebia Complex [SZEDERKÉNYI 1998]). Subsequently the Variscan phase of banded arrangement, the oldest Palaeozoic–Mesozoic formations (the age of which can be determined with certainty) are the Permian clastic sequences of the Alpine cycle, and the rhyolite (Gyűrűfű Rhyolite Formation) of Permian age, too, which got to the surface in the continental rift-valleys. The German-type Lower Triassic siliciclastic formations (Jakabhegy Sandstone Formation) — deposited in fluvial–shallow-marine environment — are widespread in the Kiskunság as a whole. The deposition of clastic beds was later gradually replaced by carbonate sedimentation — the transition is indicated by dolomarls, dolomitic marly shales. These are most commonly overlain by Middle Triassic silty shales (Patacs Aleurolite Formation) and shallow-marine carbonates (Szeged and Csanádapáca Dolomite) due to the progress of Triassic transgression and the subsidence of the carbonate ramp.

The evolution of the Mecsek and the Villány–Bihor Unit differed in the Late Triassic: while almost continuous Upper Triassic – Jurassic sequences are found in the former, thin and strongly discontinuous sequences are known from the latter area. Upper Triassic – Lower Jurassic, coal containing siliciclastic beds (Mecsek Coal Formation) occur in patches in the eastern part of the area. Transgression and gradual deepening of the sea is marked by the deposition of the "spotted marl" (Fleckenmergel) series covering the coal beds; the initially sandy marl, marly sandstone beds later became replaced by pelitic, spotted calcareous marls with increasing carbonate content (Vasas Marl Formation, Hosszúhetény Marl Formation). The Middle and Upper Jurassic is characterised by pelagic limestone, cherty limestone beds (Óbánya Limestone Formation, Kisújbánya Limestone Formation). The similarity of the Malmian sedimentation in the Mecsek and the Villány–Bihor Unit suggest that the connection between the two areas was restored (NÉMEDI VARGA 1998).

The Mecsekjánosi Basalt Formation — produced by the submarine rift volcanos in the Early Cretaceous — is significantly widespread in the Mecsek Unit. The Magyaregregy Conglomerate of near-shore facies is derived from the denudation of the basalt, and usually rests on the volcanic formations. Towards the basin it is replaced by the pelagic Hidasivölgy Marl. As the Late Jurassic sedimentary basin became more shallow, in the Villány–Bihor Unit a shallow-marine platform came into being in the Early Cretaceous. It is represented by the Nagyharsány Limestone of Urgon facies.

The formation of the structure of the basement characterised by folds, nappes and thrusts started in the Cenomanian Age (Császár 2002), and culminated in the Coniacian. In the foreland of the nappe fronts pelagic basins came into being, in which clastic–carbonate sediments were deposited (Bisse Marl, Gátér Marl, Vékény Marl, Bóly Sandstone).

In the course of the orogeny following the nappe formation significant elevation and denudation took place. Sediments of the Senonian sedimentary cycle unconformably overlie the pre-Senonian basement both in the Mecsek and in the Villány–Bihor Unit, and cover the compressional structures. The base of the Senonian succession is made up of coarse clastic rocks (Szank Formation), the transgressional sequence above the latter is built up by formations of pelagic basin facies (Csikéria Marl, Izsák Marl, Bácsalmás Formation) (Haas 1998).

Basin fill sediments

In the Palaeogene the Tisza Mega-unit area became dry land on which denudation took place. The Neogene sequence rests on the basement with a considerable unconformity. During the Neogene new, primarily extensional tectonic phases commenced. The pre-Pannonian Cenozoic formations are made up predominantly of Miocene continental and shallow-marine clastic sedimentary formations occurring in patches and characterised by varying thicknesses.

The red and variegated clay, aleurolite, sandstone and conglomerate formations deposited mainly in continental–fluvial accumulation environment represent the Madaras Member of the Lower Miocene (Eggenburgian–Ottnangian) Szászvár Formation. The first main extensional movements can be dated to the Ottnangian – Early Badenian: the troughs opening up along the low-angle normal fault were formed in the course of the rejuvenation of extensional tectonics along the Cretaceous nappe boundaries of the Tisza Mega-Unit. In the troughs between the diverging basement blocks the continental sedimentation was gradually replaced by marine sedimentation.

A total of five detectable sub-cycles took place in the Middle Miocene (Karpatian – Lower Badenian) with Mediterranean relationships and the sedimentation of littoral, nearshore, open-water formations (Kiss et al. 2010a). In the Karpatian Age, abrasion shoreline formations (gravel, conglomerate) were deposited at the margins of the continental terrains; towards the basin in the Kiskunhalas Trough they interfinger with cyclic schlier successions (Kiskunhalas Formation). No volcanism took place in the area, but some tuff strips (Tar Dacite Tuff Formation) indicate the activity of distant volcanos.

The Badenian sedimentation took place in an archipelago environment with very diverse facies. The Abony Formation consists of upward-fining abrasion basal conglomerate and upward-fining gravelly sandstone, sandy, porous limestone appearing at the base of the Badenian transgression. In the further periods of the Middle Miocene the area was restricted from the Mediterranean and only a connection to the SE toward the Black Sea and Caspian Sea was established, which can be followed by faunal elements. The Upper Badenian–Sarmatian sediments reflect a slight regression: coarse clastic, fine clastic and carbonate facies also occur. The molluscan, lithothamnium sandstones, calcareous sandstones of the Ebes Formation are considered as marginal and fringing reefs formed in shallow-water, nearshore facies. The archipelago facies was still characteristic. The Deszk horizon (gravelly coarse sandstone–conglomerate) observed on the Algyő–Ferencszállás–Kiszombor basement high ridge indicates that the area used to be an island. The Sarmatian sediments indicating poorly ventilated, reductive conditions occur only sporadically in small thicknesses (Tompa, Bugac, János-

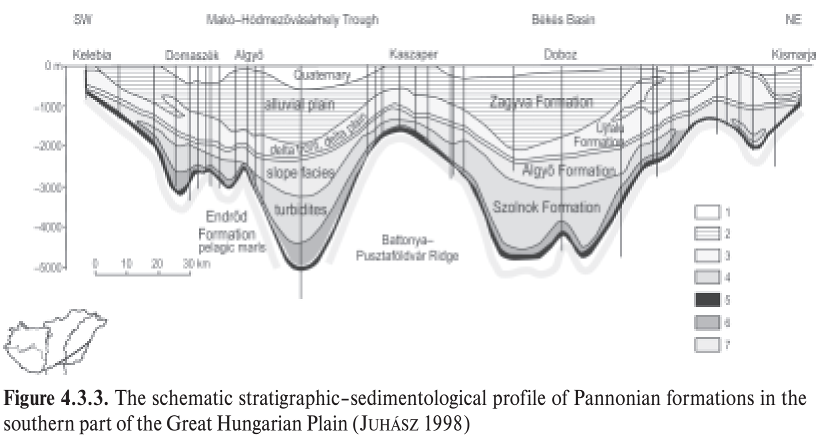


Figure 4.3.3. The schematic stratigraphic–sedimentological profile of Pannonian formations in the southern part of the Great Hungarian Plain (Juhász 1998)

Legend: 1. fine-grained sandstone; 2. medium-grained sandstone; 3. siltstone; 4. argillaceous marl; 5. calcareous marl; 6. conglomerate; 7. Neogene basement

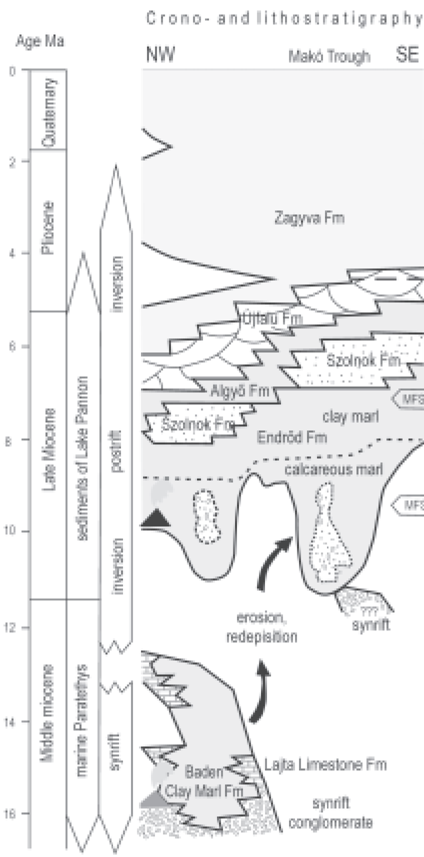


Figure 4.3.4. Chrono- and lithostratigraphic classification of the basin fill sediments in the Makó Trough and the surrounding areas (adapted from Sztanó et al. 2012)

halma). The gravelly, coarse grained sandstone deposited at this time on the Algyő Ridge is of littoral facies. The Sarmatian–Pannonian transition is continuous in some places.

The Pannonian formations (Figures 4.3.3–4.3.4) are transgraded at some places directly over the Palaeozoic–Mesozoic basement complex, as can be seen on the AL–41 seismic profile, showing the edge of the Makó–Hódmezővásárhely Trough (Figure 4.3.5). Elsewhere they overlie the sporadically occurring older Miocene formations, as in the Kömpöc-Mindszent depression seen on the Reg–7 profile (Figure 4.3.6), and in the Kiskunhalas Trough (Figure 4.3.7), where the thickness of the pre-Pannonian Miocene formations reaches several thousand metres.

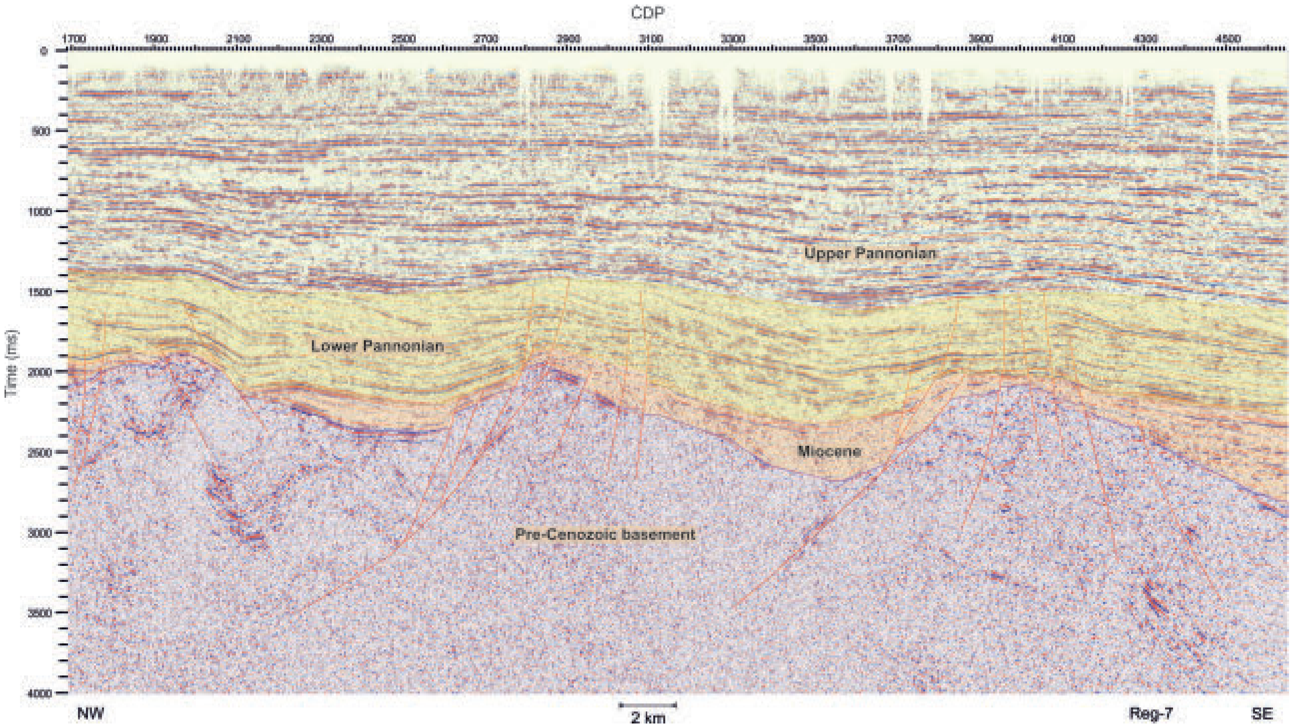


Figure 4.3.5. The Al-41 seismic section of NW-SE direction in the Szeged Basin. (The trace line can be seen in Figure 1, red lines indicate the faults)

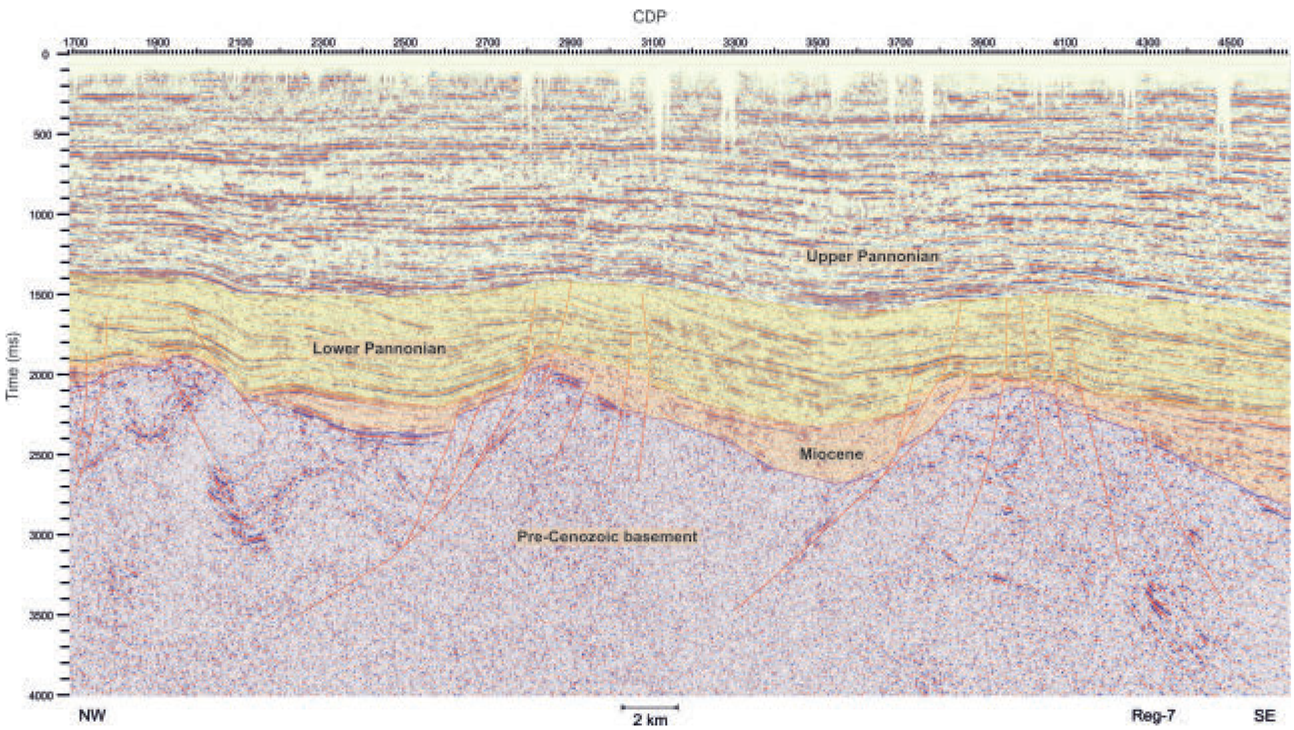


Figure 4.3.6. The Reg-7 seismic section running NW-SE in the middle part of the exploration area. (The trace line can be seen in Figure 1, red lines indicate the faults)

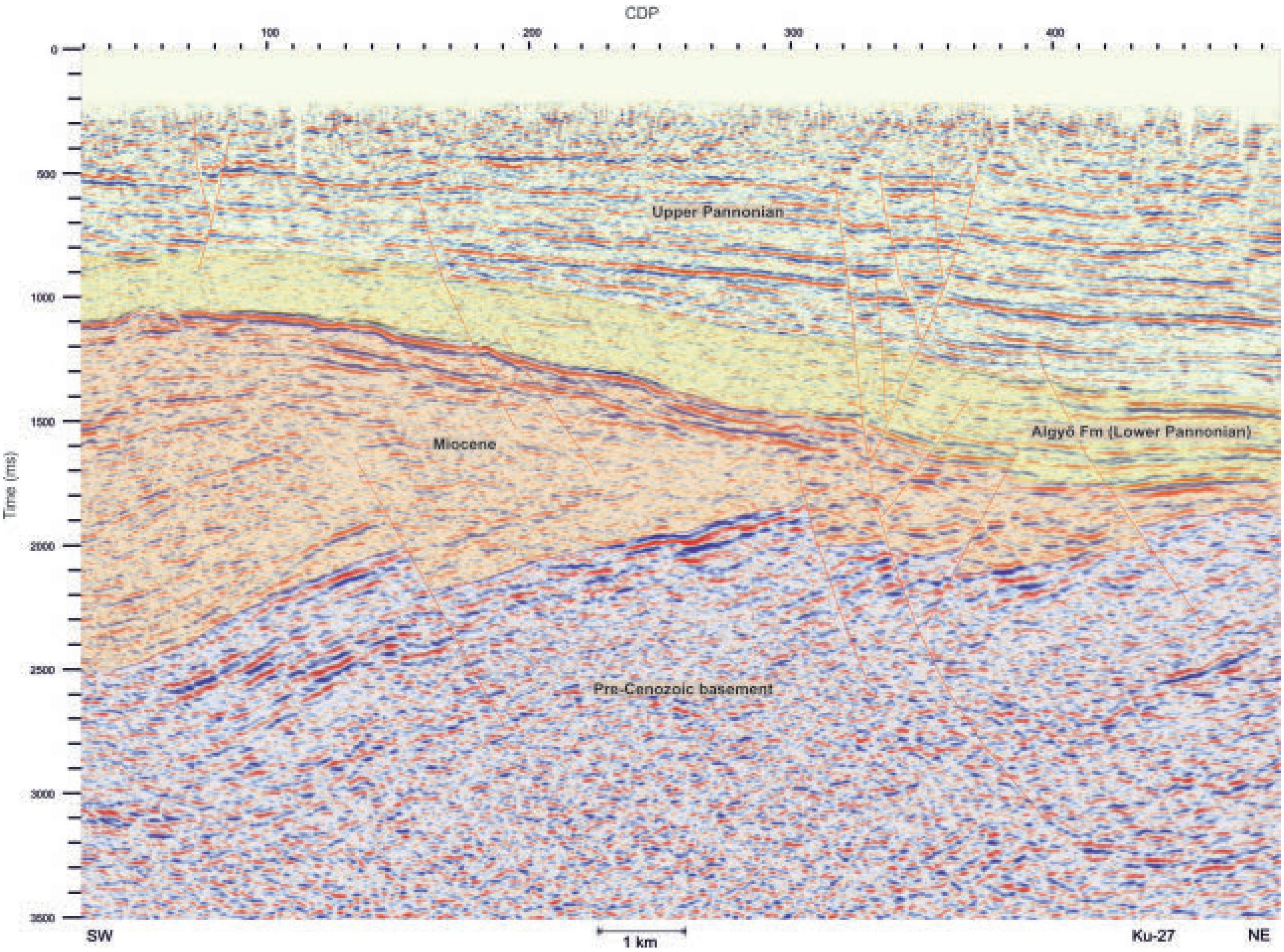


Figure 4.3.7. The Ku-27 seismic section running SW-NE in the Kiskunság (The trace line can be seen in Figure 4.3.1, the red lines indicate the faults)

The so-called "basal marls" form the Pannonian base. They are of a condensed sequence and from a lithostratigraphic point of view can be divided into different members (Endrőd Marl Formation). They were deposited far from the supply areas in the basins, and thicken out north-westward in the Makó Trough, where the basement is thought to descend. The oldest member in the Makó Trough overlying the basement is the argillaceous marl, transected by the Makó–7 and the Hód–I wells in a thickness of approximately 450 metres; at the bottom it contains metamorphic pebbles. Its age is uncertain, but according to recent studies it is thought to be of (Karpatian–) Early Pannonian, with a sedimentation rate of approximately 450 m / 400 ka (SZABÓ et al. 2010).

The boundary of the next unit, the Tótkomlós Calcareous Marl Member can be determined on the basis of the increased carbonate and organic matter contents.

The maximum thickness is approximately 730 m (in the Hód–I well). The lower part is the so-called "basal conglomerate", in which intercalations made up of sediments of different grain size can be found; they comprise pebbles of a diameter reaching up to 10 centimetres (originating from islands). These sediments were deposited from debris flow close to the toe of the slope. This lower part can be classified into the Dorozsma Gravelly Marl Member. In the upper part only thin intercalations made up of sand–aleurite sized grains originating from turbidity flows are typical; this section is thought to belong to the Vásárhely Marl Member.

The "basal conglomerate" and the calcareous marls with very high carbonate content were accumulated at a rate of 430 m / 200 ka — the accelerated sedimentation is most probably due to the gravitational mass movements (SZABÓ et al. 2010).

Simultaneously with the subsidence of the basin, the coarse clastic deposits become more and more subordinate. The next stratigraphic unit, i.e. the Nagykörü Clay Marl Member, develops as the quantity of carbonate declines. In its upper part the coarse-grained intercalations (derived from low-density sandy turbidity currents) disappear and clay content increases; this indicates a more distant source area. The rate of sediment formation is reduced accordingly: 300 m / 900 ka (SZABÓ et al. 2010). The area was covered with water by that time, to an estimated depth of 1 km.

The turbidite succession of the Szolnok Sandstone Formation overlies the deep-water marls, consisting of alternating layers of fine-grained sandstone and argillaceous marl. The formation is thin on the elevated ridge, but it is up to 1,000 metres thick in the Makó Trough. Simultaneously with the deposition of the Szolnok Formation, south of the Makó Trough, the turbidity currents could have been stopped by an underwater high. They could have passed through this barrier as the

filling-up process progressed — this is why the formation is so thick in the trough. Twenty one sandstone groups (30–40 sand bodies) are known in Algyő, deposited in an offshore, open-water environment under the wave base. This succession interfingers with the clayey lithofacies of the Nagykörü Member (Kiss et al. 2010a).

The Szolnok Sandstone Formation is overlain by the Algyő Formation, which was deposited on the basin slope of an angle of 5–20°; simultaneously with the building-up of the slope, the Algyő Formation becomes increasingly younger.

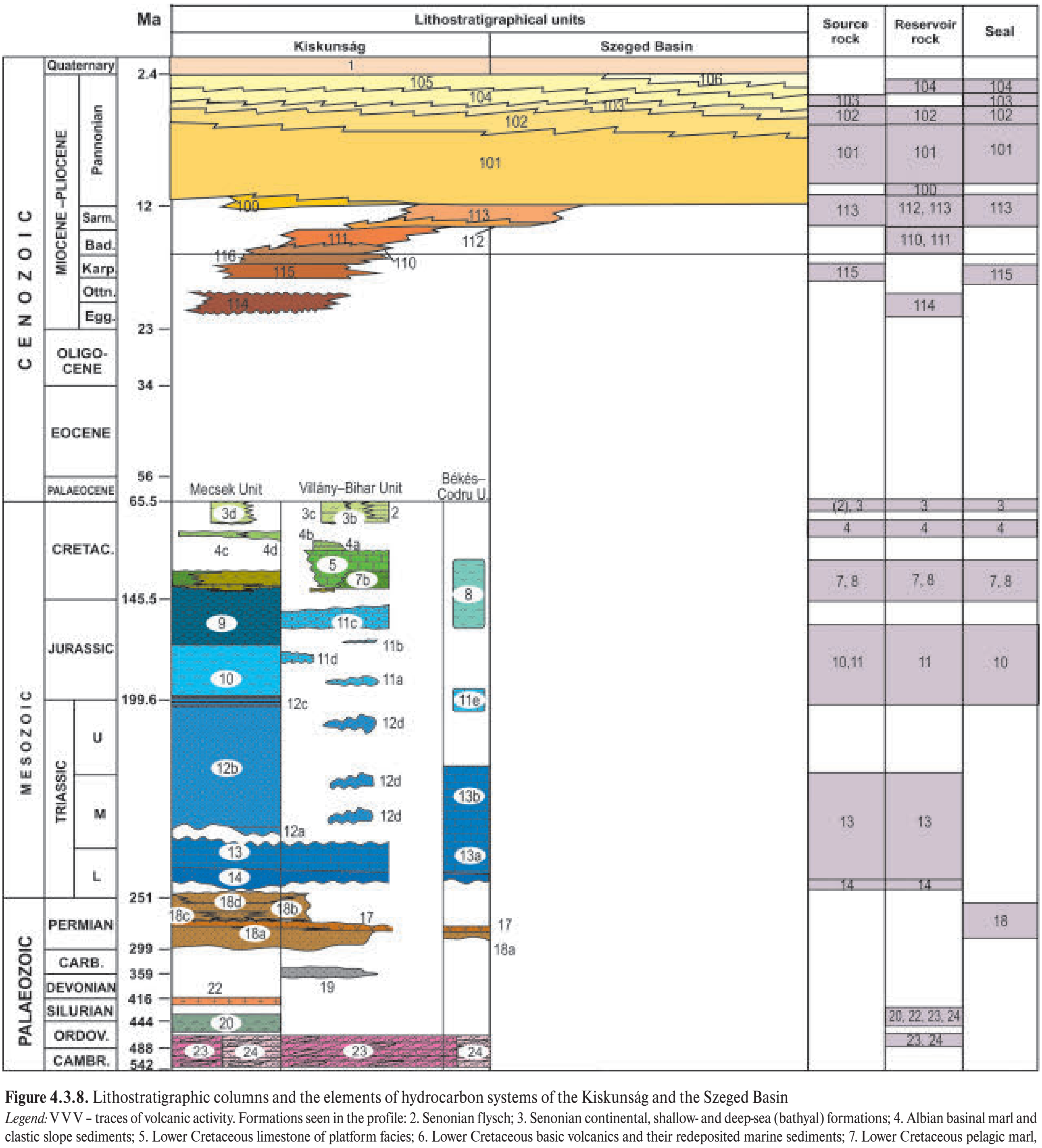


Figure 4.3.8. Lithostratigraphic columns and the elements of hydrocarbon systems of the Kiskunság and the Szeged Basin

Legend: V V V – traces of volcanic activity. Formations seen in the profile: 2. Senonian flysch; 3. Senonian continental, shallow- and deep-sea (bathyal) formations; 4. Albian basinal marl and clastic slope sediments; 5. Lower Cretaceous limestone of platform facies; 6. Lower Cretaceous basic volcanics and their redeposited marine sediments; 7. Lower Cretaceous pelagic marl, limestone; 8. Jurassic – Lower Cretaceous pelagic limestone, marl; 9. Middle Jurassic – Lower Cretaceous pelagic limestone, cherty limestone; 10. Lower–Middle Jurassic pelagic, fine siliciclastic formation; 11. Jurassic shallow-marine and condensed pelagic limestone formation; 12. Upper Triassic – Lower Jurassic coal-bearing, siliciclastic formation; 13. Middle Triassic shallow-marine, siliciclastic and carbonate formation; 14. Lower Triassic siliciclastic formations of fluvial and delta facies; 17. Permian rhyolite; 18. Permian clastic formation of continental facies; 19. Upper Carboniferous clastic formation of continental facies; 20. Early Palaeozoic low-grade metamorphic formations; 22. Variscan granitoid rocks; 23. Variscan metamorphic formation (gneiss, mica, amphibolite); 24. Variscan crystalline rocks without subdivision; 114. Eggenburgian–Ottnangian clastic formation of continental– fluvial facies; 115. Karpatian open-water siliciclastic beds; 116. Karpatian airfall dacite tuff; 110. Lower Badenian abrasion basal breccia; 111. Middle Badenian shallow-marine biogenic limestone; 112. Sarmatian transgressive basal debris; 113. Sarmatian shallow-marine carbonate and siliciclastic beds; 100. Pannonian littoral conglomerate, sandstone; 101. Pannonian open-water calcareous marl, marl, argillaceous marl; 102. Pannonian beds of deep-water, turbiditic origin; 103. Pannonian sediments deposited in underwater slope environment; 104. Pannonian siliciclastic formation of littoral origin; 105. Pannonian siliciclastic formation of fluvial and lacustrine origin; 106. Pannonian formation of fluvial facies; 107. Quaternary sediments

Since the gravity movements start on the slope, mainly clay was deposited here with a low sedimentation rate, but occasionally sandstone bodies — deposited in channels — are also embedded in the sequence.

The so-called "Lower Pannonian" succession (Békés Conglomerate Formation, Endrőd Marl Formation, Szolnok Sandstone Formation, Algyő Formation) accounts for a thickness of 600–800 metres in the elevated areas, but may reach as much as 1,500–2,000 metres thickness in the direction of the Makó Trough.

The sedimentation took place in an inshore environment along the basin margins, resulting in the deposition of predominantly delta sediments. The so-called "Upper Pannonian" succession (Újfalu Formation, Zagyva Formation) accounts for a thickness of 600–800 metres in the elevated areas, but may reach as much as 2,000 metres in the direction of the basins. In the Danube–Tisza Interfluve the Zagyva Formation thins out gradually towards the margins.

The area in the Quaternary belonged to the south-eastern part of the Danubian tectonic trough. Elevation and erosion took place on the basement high ridges due to SW–NE compression. Intensive subsidence of the Makó Trough and the related sub-basins suggests that the thickness of the Quaternary formations in the area, predominantly the coarse-grained sediments, deposited as the alluvial cone of the Danube, approaches 600–700 metres. The theoretical stratigraphic columns for the area are shown in Figure 4.3.8.

An overview of hydrocarbon geology

Hydrocarbon fields of national importance can be found in the Szeged Basin: Algyő, Ferencszállás, Kiszombor, Szeged, Üllés, Forráskút. The most important hydrocarbon accumulation zone of the Danube–Tisza Interfluve in the Kiskunság is related to the reverse fault zone running in the Baja–Kiskunfélegyháza line, with the following key sites: Kiskunhalas, Tázlár, Kiskunmajsa, Szank (Figure 4.3.9).

Source rocks

Sources of Szeged–Kiskunság region oils are possibly Middle Miocene marls (Baden Fm, Badenian age) and the Upper Miocene (Lower Pannonian age) Tótkomlós Marl Member of the Endrőd Formation, especially along with Jurassic shale in the basement of Kiskunság (MILOTA 1991, BADICS, VETŐ 2012).

Carbon dioxide may be released from the very high maturity metamorphic carbonates of the pre-Cenozoic basin basement — gases containing more than the 80% CO_2 migrate from the deep basin zones along large listric faults. Due to the heat impact a mixture of N_2 and CH was released in the environment of the igneous masses from the organic matter of the poorly metamorphic rocks and coal seams, which accumulated by migrating into the still empty parts of the reservoir traps. The source rock of the higher inert containing gases is presumably Lower Cretaceous limestone, calcareous marl.

The low amount organic matter of Triassic carbonate rocks of the pre-Cenozoic basement is considered to be overmatured. The carbon dioxide gas providing the CO_2 content of natural gases in the hydrocarbon reservoirs accumulated on the basement high ridges may be partly originating from the thermal metamorphosis of the structurally low positioned carbonate beds (KERTAI 1972, CLAYTON, KONCZ 1994a). The Jurassic argillaceous marls could have generated substantial amount of hydrocarbons provided they were mature enough.

The Miocene and Pliocene rocks contain gas yielding organic matter derived basically from plants of terrestrial origin. The Badenian, and the Sarmatian stage sediments have varying degree of hydrocarbon potential.

Condensed sequences of the "Lower Pannonian basal marls" (Endrőd Marl Formation) represent the most important source rocks of the crude oil and natural gas in the basin. The highest organic matter content is in the finest grain size marls that appear in the base level of the formation (Tótkomlós Calcareous Marl Member). These marls have been deposited under anoxic conditions favouring the preservation of the organic matter. Total organic carbon content (TOC) ranges from 2 to 5 wt% in this formation and mainly Type III kerogen is characteristic, but occasionally Type II kerogen is also enriched in it, which is beneficial for the generation of oil. The succession is currently in the oil window or in the wet gas zone in the deep basins. The Endrőd Marl in the Makó Trough exceeds occasionally the 1,000 metres thickness as well; in other words, it could have provided a substantial amount of organic matter for the hydrocarbon generation in the trough.

The organic matter contents of the fine grained sediments in the Szolnok Sandstone and in the Algyő Formation is usually low, and can only be taken into account guardedly as a source rock. Although the fine-grained sediments of the Upper Pannonian sequence contain the most significant organic matter content; due to the shallow burial and low temperature their maturity is also low, therefore in these horizons one can only count on hydrocarbons of biogenic origin. (SZABÓ et al. 2010).

Three types of potential source rock can be identified in the area:

— Lower and Middle Jurassic argillaceous marl succession;

— Middle Miocene Badenian–Sarmatian stage argillaceous marl, marl, calcareous marl sequence;

— Upper Miocene Lower Pannonian marls and calcareous marls.

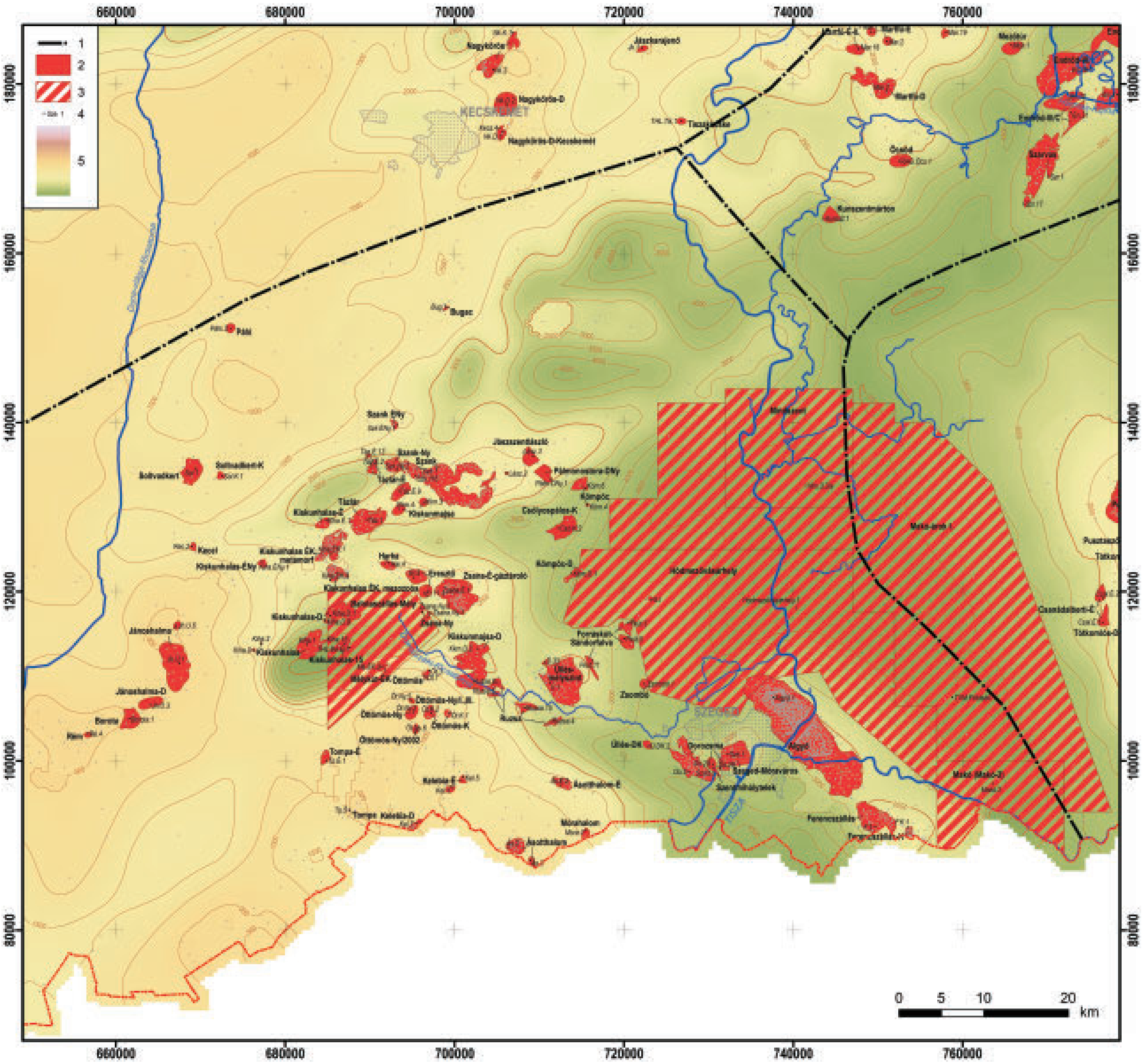


Figure 4.3.9. Location of hydrocarbon fields and the depth of the pre-Cenozoic basement in the Kiskunság and Szeged Basin area
Legend: 1. Boundary of the sub-basin area; 2. Conventional hydrocarbon field, 3. Unconventional hydrocarbon mining plot; 4. Discovery well; 5. Depth of the pre-Cenozoic basement

Their relative significance in some lesser area varies as a function of their occurrence and subsurface depth. Locally important source rocks may be the Upper Triassic – Lower to Middle Jurassic open sea marls (Komló Calcareous Marl Formation) around Soltvadkert; and the Lower Cretaceous formations at Tompa North. Presumably the Upper Cretaceous, Karpatian stage fine clastics and the Badenian shales are the source rocks of the hydrocarbons in the surroundings of Kiskunhalas.

Migration

Hydrocarbons can be found in the area that were generated mainly from the pelitic–carbonate sediments accumulated in the deep basins surrounding the Palaeozoic–Mesozoic basement high ranges (for instance in the Makó–Hódmezővásárhely Trough, the Szeged Basin or in the Kiskunhalas Basin). They migrated from the basin depths towards the top zones of the higher structural blocks. Regionally a migration route from the east–south-east to the west–north-west can be observed. Oil and gas migration takes place even today in the deep basins partly of compaction origin, and partly associated with the generation of hydrocarbons towards the elevations.

The main pathways of hydrocarbon migration are as follows: (1) the weathered top of the pre-Cenozoic crystalline basin basement (the so-called lower migration zone); (2) the top of either the Mesozoic or the Miocene succession overlying the

basin basement, or the base of the Middle Miocene or Upper Miocene Lower Pannonian succession (middle migration zone); (3) Middle Miocene – Pannonian siliciclastic sedimentary layers (upper migration zone). Vertical migration along the faults might have also played a role in the charging of the reservoirs beside primary and secondary lateral migration, which could have been more important in the case of reservoirs in the Pannonian succession.

In the case of the Szeged–Kiskunság region, locally and regionally, migration along carrier beds through semipermeable sediments is present, with faults playing a significant role.

In the case of Algyő, Szank, and Üllés, the specific trend is that the shallower the depth, the lower the oil density. This may have been caused by a separation mechanism of oil migrating through fine-grained shaly sediments. The steep trends of Dorozsma, Ruzsa, and Kiskunhalas can have been caused by the oil migrating along tectonic surfaces. In the opposite trend of Öttömös, post-trapping alteration (degassing, water washing, and biodegradation) of crude oil can be supposed because of the relatively near-surface position. In some cases, in the Algyő Upper Pannonian reservoirs, the dissolved gas content of oils is much higher than in other oils in this field. Otherwise, the distribution of dissolved gas content versus depth and dissolved gas content versus oil density trends is normal. This means the greater the depth, the higher the dissolved gas content; the lower the oil density, the higher the dissolved gas content (KOVÁCS ZS., ZILAHI 2018).

Reservoir rocks

Reservoirs of this region are situated in varied Palaeozoic–Mesozoic magmatites and carbonates (Öttömös, Dorozsma, Kiskunhalas, Ruzsa, and Üllés fields), Middle Miocene conglomerates, calcareous marl, coarse-grained limestone (Öttömös, Kiskunhalas, Dorozsma, Ruzsa, Szank, and Szank West fields), Upper Miocene (Lower Pannonian), conglomerates, turbiditic, and delta slope sandstone (Algyő, Dorozsma, Ferencszállás, Szank, and Ruzsa fields), and Upper Miocene (Upper Pannonian) sandstone (Algyő, Dorozsma, and Öttömös fields).

The important reservoir rocks of the basement complex (Figure 4.3.10) are the weathered surface and fractured upper zone of the Early Palaeozoic (Variscan) metamorphites and Permian rhyolite, rhyolitic tuff, as well as fractured Lower Triassic sandstone and Middle Triassic fractured, brecciated dolomite. The Lower Jurassic limestone, the Lower and Upper Cretaceous limestone, marl and calcareous sandstone are also good reservoir rocks at some places.

The stratigraphic traps associated with the unconformity surface of the base Miocene sediments (lithothamnium limestone, calcareous sandstone and clastic successions) covering the basement are also important. The Middle Miocene Badenian–Sarmatian stage carbonates and the fine or coarse clastic sediments are good reservoir rocks. The Lower Pannonian basal conglomerates and basal sandstones (Békés Conglomerate Fm) deposited close to the shoreline in isolated parts are known as very good reservoir rocks. The fractured zones of the Endrőd Marl Tótkomlós Member are good hydrocarbon reservoirs. Hydrocarbons are accumulated in some reservoirs in Lower Pannonian volcanic rocks in the Üllés and Ruzsa fields.

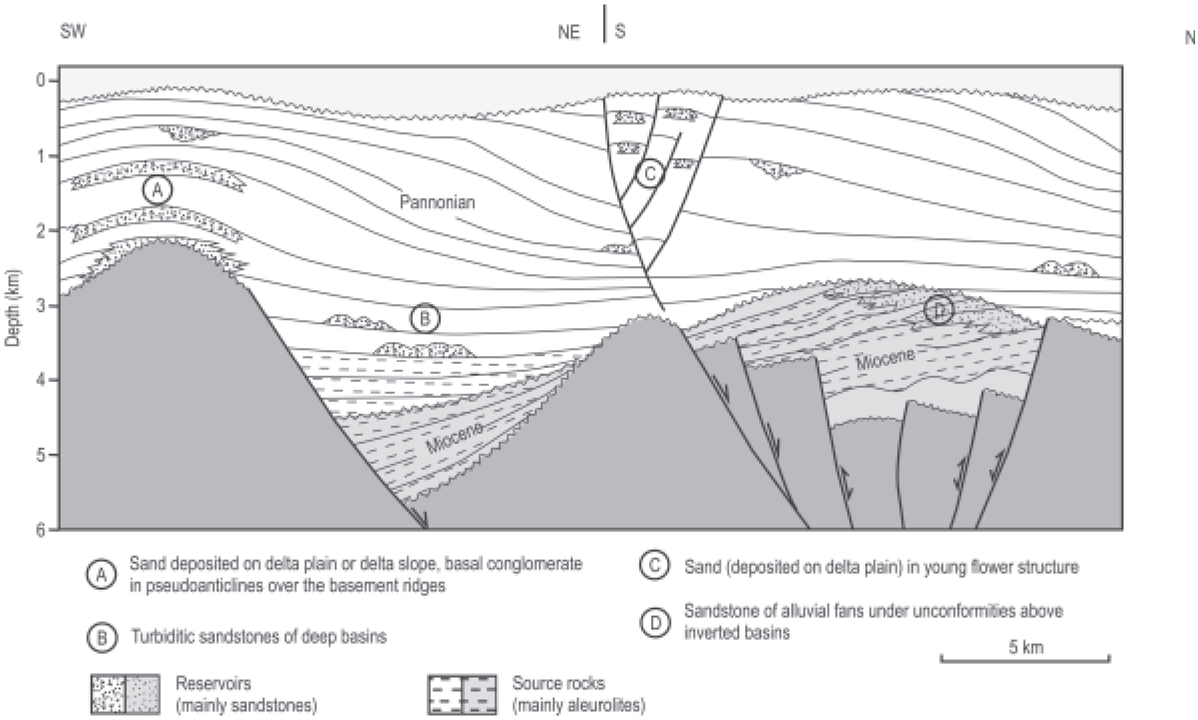


Figure 4.3.10. Theoretical cross-section to show the hydrocarbon system of the Neogene basin fill at the Great Hungarian Plain (HORVÁTH, TARI 1999)

Locally the turbidites of Szolnok Sandstone Fm and the sandy parts of the fine particle sediments in the Algyő Fm are good reservoir rocks. These two formations store 12% of the hydrocarbons in the Algyő–Ferencszállás basement high range reservoirs. Sandstones of the Újfalu Formation store nearly 80% of the hydrocarbons in Algyő (Kiss et al. 2010a). Mostly biogenic gases and partly thermogenic gases were accumulated in the delta flats facies point bar and river bed sandstones and poorly consolidated sand bodies derived from the above mentioned source rocks.

Porosity of the Pannonian sand and sandstone beds is mostly primary, intergranular nature and generally significant, values usually vary in a range of 15–32%. Where calcareous marl is also part of the reservoir beside the sandstone, the porosity declines accordingly. In general, however, porosity of the Lower Pannonian sandstones is around 15–20%. Because of the lesser cement content and slighter compaction of the Upper Pannonian sands the porosity is greater on average, with most of the values in the 20–30% range.

Seal rocks

Seals of the reservoir formations are clays and argillaceous marls building up the bedrock and cap rock of the reservoir rocks and are impermeable under hydrostatic pressure conditions: argillaceous marls interrupting the sandstones, or — in the case of the lithologic traps — the reservoir itself, become impermeable, clayey or thinned out.

The thick Lower Pannonian pelitic sediments, argillaceous marls covering the pre-Cenozoic basement and the Middle Miocene formations are excellent seals (Figure 4.3.10). Similar formations can be found between the Lower and Upper Pannonian sandstones as well. In certain areas the Permian shales (Csólyospálos East), the Jurassic shale-bearing horizons, Cretaceous shale formations (Öttömös), the Karpatian stage argillaceous marl (Kiskunhalas), and Miocene fine grained clastic horizons are also important as cap rocks. The Algyő Formation with the predominantly clay-bearing facies is a regional Pannonian seal formation, which, however, does not provide a full closure: sandstones of the channels on the delta slope may provide connections towards the delta plains.

Trapping

Hydrocarbon occurrences of commercial value are often associated with elevated Precambrian and/or Mesozoic crystalline and carbonate basement high ranges and blocks, which constitute a stratigraphic trap together with their covering cap rock. In case of elevated morphological positions the Neogene carbonate–clastic sediments form pseudoanticline traps and thinning/pinching out lithologic traps. In the Middle Miocene and the Pannonian rocks the lateral lithologic variability could have led to the formation of stratigraphic/lithologic traps. Structural traps are subordinated, associated mostly with strike-slip faults of displacement zones, or with fault bordered slight domes formed as a result of the differentiated compaction.

Typical trap types of the area are as follows:

— traps formed in the pre-Cenozoic basement rocks along unconformity surface;

— structural traps of the Mesozoic formations;

— Middle Miocene reservoirs in domes formed with differential compaction or accumulated along unconformity surfaces;

— reservoirs formed in the compaction domes of Pannonian sandstones, which are partly of half-graben structures related to faults;

— stratigraphic traps, combined structural-stratigraphic-traps in Middle Miocene coarse-clastics and Pannonian sandstones;

— unconventional accumulations of deep basins.

Hydrocarbon occurrences of the Kiskunság and Szeged Basin

Kiskunság

Data characterising the discovered reservoirs (hydrocarbon composition, calorific value etc.) basically are originated from the National Mineral Raw Materials and Geothermal Energy Resources Register of the Mining and Geological Survey of Hungary (MBFSZ), in other cases the source is indicated.

Borota. The Borota–1 well is a multiple free gas reservoir discovered in 2001. The depth of GWC (gas-water contact) is 397.5 metres below sea level (bsl). The reservoir rock is Middle Miocene calcareous sandstone (Ebes/Lajta Formation). The combustible part of the accumulated natural gas is 82.5%, the calorific value is 29.6 MJ/m^3. The methane (CH_4) content is 82.3%, the carbon dioxide (CO_2) 6.4%, the nitrogen gas (N_2) 11.1%.

Bugac. Oil reservoir with dissolved gas, discovered by the Bug–1 well in 1970. The reservoir rock is Middle Miocene

Sarmatian conglomerate. The OWC (oil water contact) is at 1,051 m bsl. The oil is paraffinic, its density is 834 kg/m^3. The combustible part of the dissolved gas is 90.2%, the calorific value is 40.6 MJ/m^3. The CH_4 content is 82.4%, CO_2 3.7%, N_2 6.1%. The C_{5+} content (straight chain hydrocarbon compound containing more than five carbon atoms) of the dissolved gas is 70 g/m^3.

Csólyospálos East (Csólyospálos-Kelet in Hungarian). Multiple free gas reservoir in the fractured Variscan metamorphic basin basement, discovered by the Csó-K–2 well in 1999. The OWC depth of the reservoir is 3,424.5 m bsl, the vertical closure is 325 metres. The combustible part of the natural gas is 95.4%, the calorific value is 39.7 MJ/m^3. The CH_4 content is 85.0%, CO_2 3.5%, N_2 1.1%, the C_{5+} content is 46 g/m^3.

Eresztő. The Er–5 well discovered an oil reservoir with gas cap in 1976 (OWC 1,788 m bsl, vertical closure 104 m), then a separated free gas reservoir was found in the Er–11 well in 1980 (GWC was also 1,788 m, vertical closure 56 m). The reservoir rocks of the oil reservoir are the Lower Cretaceous basin basement rocks and the overlying Middle Miocene calcareous sandstone. The oil is paraffinic, its density is 870 kg/m^3. The sulphur content is 1.1%. Dissolved gas content 60 m^3/m^3, the combustible part of the gas is 86.4%, the calorific value is 33.8 MJ/m^3. The CH_4 content is 81.1%, CO_2 6.5%, N_2 7.1%, C_{5+} content 54 g/m^3.

The reservoir rock of the free gas reservoir is also Lower Cretaceous, fractured basement rock and Middle Miocene limestone. The combustible part of the accumulated natural gas is 89.4%, the calorific value is 35.4 MJ/m^3. CH_4 content 82.3%, CO_2 6.4%, N_2 4.2%, C_{5+} content 2 g/m^3.

Harka. Free gas occurrence in the neighbourhood of Eresztő, the discovery well was the Har–4 (1975). The GWC depth is 1,740 m bsl, the vertical closure is 50 m. The reservoir rock of the gas is the Miocene porous limestone and the Lower Cretaceous, fractured basement rocks. The combustible part of the natural gas is 79.5%, the calorific value is 30.1 MJ/m^3. CH_4 content 76.3%, CO_2 10.9%, N_2 9.6%, C_{5+} content 75 g/m^3.

Jánoshalma. Discovery wells are the Jh-Ú–1 (1982) and the Jh-Ú–6 (1983). The Jh-Ú–1 well drilled two free gas reservoirs pinching out on the bottom, the GWC depths are 405 and 442.5 metres bsl. The reservoir rocks are Miocene, Badenian porous limestone and sandstone (lower reservoir), as well as the fractured Palaeozoic basement rocks. The combustible part of the upper reservoir gas is 86.8%, the calorific value is 31.1 MJ/m^3, CH_4 86.8%, CO_2 4.1%, N_2 9.2%. The combustible part of the gas of the lower reservoir is 90.8%, the calorific value is 32.5 MJ/m^3. CH_4 90.7%, CO_2 0.6%, N_2 8.6%. Condensate content is not known.

The OWC depth of the small oil reservoir explored by the Jh-Ú–6 well is 465 m bsl. The reservoir is Palaeozoic, fractured metamorphite. The accumulated oil is naphthenic, its density is 991 kg/m^3. The sulphur content is high, 4.5%. The low volume combustible part of the dissolved gas is 95.2%, the calorific value is 34.3 MJ/m^3. The CH_4 content is, 94.8%, CO_2 0%, N_2: 4.8%. Condensate content is not known.

Jánoshalma South (Jánoshalma-Dél). The single free gas reservoir was discovered by the Jh-Ú–3 well in 1982 at a depth of 416.5 m bsl (GWC). The reservoir rock is Miocene sandstone. The combustible part of the natural gas is 89.1%, the calorific value is 32 MJ/m^3, CO_2 1.9%, N_2 9.0%.

Kecel. Oil reservoir formed in the Lower Pannonian volcanics (Kecel Basalt Formation) drilled by the Kec–2 well in 1972, at a depth of 972.5 m bsl (OWC). The oil is of intermediate type, its density is 923 kg/m^3, combustible part of the dissolved gas 94.5%, calorific value 37.7 MJ/m^3. The CH_4 content of the gas is 89.6%, CO_2 0%, nitrogen content (N_2) 5.5%.

Kiskunhalas. The Kiha–1 discovery well explored five free gas reservoirs in the field discovered in 1967, numbered I–V from top to bottom. The lower two accumulations are situated in the Miocene, Karpatian stage sandstone reservoir rock, and can be found at a depth of 1,528 and 1,794 m bsl (GWC), respectively. The combustible part of the lower reservoir (V) gas is 97.6%, the calorific value is 43.9 MJ/m^3, CH_4 84.0%, CO_2 1.6%, N_2 0.8%. The condensate content is 97 g/m^3. The combustible part of the natural gas accumulated in the upper reservoir (IV) is 98.4%, the calorific value is 39.8 MJ/m^3. CH_4 content 90.9%, CO_2 0.8%, N_2 0.8%, C_{5+} 36 g/m^3.

The reservoir rock of the upper (II–III) accumulations is Middle Miocene, Badenian conglomerate, that of the uppermost (I) is sandstone. Their depths are 950, 1,000 and 1,011 metres bsl (GWC), respectively. The combustible part of the natural gases is 95.7–97.9%, their calorific values is 36.3–37.1 MJ/m^3. The CH_4 content is 90.5–94.0%, CO_2 0–0.4%, N_2 1.9–4.2%. The C_{5+} content in the reservoir II is 4 g/m^3.

The Kiha–2 and the Kiha–9 wells explored stand-alone satellite reservoirs to the west of the field. One small scale oil and one natural gas reservoir were detected.

A free gas reservoir was found in the Kiskunhalas–15 well in 2006. The reservoir rock is Middle Miocene calcareous sandstone. The GWC depth is 1,060 m bsl. The combustible part of the gas is 96.7%, the calorific value is 36.5 MJ/m^3, CH_4 content 91.8%, CO_2 1.1%, N_2 1.2%, C_{5+} 15 g/m^3.

Kiskunhalas North (Kiskunhalas-Észak). Three oil reservoirs (1, 2, 3) were identified in the Kiha-Észak–1 well in 1983. The depth of reservoir 2 is 2,300 m bsl (OWC). The reservoir rocks of accumulation in no. 1 are Triassic dolomite and dolomite breccia, that of reservoir no. 2 is Middle Miocene sandstone, and that of reservoir no. 3 is clay-bearing sandstone, also in Middle Miocene rock. Reservoirs are of the intermediate type, 850–861 kg/m^3 density oil is accumulated in them with a dissolved gas content of 67–70 m^3/m^3. The combustible part of the dissolved gas is 90–95%, the calorific value is 42–54 MJ/m^3. The CH_4 content is 57–79%, CO_2 3–9%, N_2 1–2%. The C_{5+} content is 35–255 g/m^3.

Kiskunhalas NE (Kiskunhalas-ÉK). These were divided up into field sections on the basis of the basement rock types (Variscan metamorphic or Mesozoic basement). The metamorphic part's discovery well is the Kiha-ÉK–1, drilled down in 1974. The following field sections can be separated on the metamorphic basement part:

Multiple oil reservoirs with gas caps known in the "North" field section, the OWC depth is at 2,010 m bsl. The reservoir rock is fractured metamorphite and Middle Miocene, Badenian lithothamnium limestone. The oil is of intermediate type, its density is 890 kg/m^3, the sulphur content is 0.4%, the dissolved gas content is 50 m^3/m^3. The combustible part of the cap gas is 62,6%, the calorific value is 25.2 MJ/m^3. The CH_4 content is 58.1%, CO_2 27.8%, N_2 9.6%. The C_{5+} content is 24 g/m^3.

A separated oil reservoir with gas cap is known from the well named Kiha-ÉK–21, with an OWC depth of 1,920 m bsl. The reservoir rock is Middle Miocene Badenian, porous lithothamnium limestone. The oil is of the intermediate type, its density is 890 kg/m^3, the dissolved gas content is 75 m^3/m^3. The combustible part of the cap gas is 65.2%, the calorific value is 25.9 MJ/m^3, CH_4 content 61.4%, CO_2 26.8%, N_2 8.0%, C_{5+} content 30 g/m^3.

In the Kiha-ÉK–23 well the reservoir discovered is a single dissolved gas containing oil reservoir, with a depth of 1,985 m bsl (OWC). The reservoir rock is Badenian lithothamnium limestone. The oil is of the paraffinic type, its density is 880 kg/m^3, the dissolved gas content is 50 m^3/m^3. The combustible part of the dissolved gas is 94.8%, the calorific value is 49%. The CH_4 content is 73.9%, CO_2 0.7%, N_2 4.5%. It contains 136 g/m^3condensate.

The pre-Cenozoic basement of the area in the "South" field section consists of Middle Triassic, Jurassic and Lower Cretaceous formations. The discovery well of the southern field is the Kiha-ÉK–9, drilled in 1975. The reservoir rock of the oil reservoir with gas cap discovered is Triassic dolomite. The OWC depth of the reservoir is at 1,800 m bsl. The accumulated oil is of the paraffinic type, its density is 870 kg/m^3, the dissolved gas content is 83 m^3/m^3, the sulphur content is 1.3%. The combustible part of the cap gas is 70.9%, the calorific value is 27.2 MJ/m^3, CH_4 67.2%, CO_2 19.7%, N_2 9.4%, C_{5+} content 18 g/m^3.

Kiskunhalas NW (Kiskunhalas-ÉNy). Two reservoirs are known in this occurrence which was discovered by the Kiha-ÉNy–1 well in 1990. The lower one is a dissolved gas containing oil reservoir, at a depth of 1,666 m bsl (OWC). The reservoir rock is combined, partly fractured metamorphite (gneiss) of the basement, partly the overlying Middle Miocene conglomerate. The oil accumulated is of the intermediate type, its density is 892 kg/m^3, the dissolved gas content is 32 m^3/m^3, the combustible part of the gas is 80.3%, the calorific value is 36.4 MJ/m^3, CH_4 content 65.4%, CO_2 14.3%, N_2 5.4%.

The upper accumulation is stored in a single reservoir, the depth of the OWC is 1,547 m bsl. The reservoir rock is Badenian porous limestone. The oil is of the intermediate type, its density is 887 kg/m^3. Quality of the dissolved gas is similar to that of the lower deposit.

Kiskunhalas South (Kiskunhalas-Dél). One oil and two free gas reservoirs are known in this occurrence. The Kiha-D–1 well discovered fault closed oil and free gas multiple reservoirs in 1979. The lower reservoir contains gas with condensate, its depth is 3,021 m bsl (GWC). The reservoir rock is Middle Triassic Hetvehely Dolomite and Lower Cretaceous Nagyharsány Limestone. The combustible part of the gas is 90.1%, the calorific value is 35.2 MJ/m^3, CH_4 content 80.1%, CO_2 9.2%, N_2 0.7%.

The OWC depth of the oil reservoir is at 2,670 m bsl. The reservoir rock is Upper Cretaceous conglomerate (Szank Conglomerate?), and Middle Miocene Karpatian sediments (Abony Formation?). The oil is of the paraffinic type, its density is 864 kg/m^3, sulphur content 0.17%. Dissolved gas contents is 96.3 m^3/m^3, the combustible part of which is 92%, the calorific value is 42.1 MJ/m^3, CH_4 67%, CO_2 8%, N_2 0%.

A small scale free gas reservoir was discovered by the Kiha-D–9 well in 1985, on the SW edge of the oil occurrence. The reservoir rock is Badenian calcareous sandstone (Ebes/Lajta Formation). The combustible part of its natural gas is 96.4%, the calorific value is 38.0 MJ/m^3. The CH_4 content 90.2%, CO_2 0.5%, N_2 3.1%.

Kiskunmajsa. The Kkm–3 well discovered one free gas reservoir in 1983. The reservoir rock of the accumulation is Middle Miocene sandstone. The combustible part of its gas is 94.4%, the calorific value is 39.7 MJ/m^3. The CH_4 content is 86.6%, CO_2 1.4%, N_2 4.2%, C_{5+} content 83.3 g/m^3.

The Kkm–4 well also explored a free gas deposit in 1984, the depth of the GWC is at 1,845 m bsl. The reservoir rock of the accumulation is combined, Variscan metamorphite and the overlying Middle Miocene limestone. The combustible part of the gas is 88.1%, the calorific value is 34.2 MJ/m^3. The CH_4 content is 82.7%, CO_2 3.5%, N_2 8.4%, the C_{5+} content is 14.4 g/m^3.

Kiskunmajsa South (Kiskunmajsa-Dél). The occurrence lies considerably far away from the Kiskunmajsa field, some 20 km to the south-east. The discovery well was the Kkm-D–2 well drilled in 1978. Three multiple reservoirs are known in this field. The OWC depth of reservoir no. 1 in the north is at 1,760 m bsl, the reservoir rock is Middle Triassic meta-rhyolite and the overlying Middle Miocene limestone, aleurite containing sandstone and conglomerate, in which an oil reservoir with gas cap is known. The oil is of the intermediate type, its density is 866 kg/m^3, the dissolved gas content is 100 m^3/m^3. The combustible part of the dissolved gas is 78.6%, the calorific value is 36.8 MJ/m^3. The CH_4 content 67.4%, CO_2 15.3%, N_2 6.1%, the C_{5+} content is 130.7 g/m^3 (Völgyi 1985). The combustible part of the cap gas is 74.7%, the calorific value is 29.3 MJ/m^3. The CH_4 content is 69.8%, CO_2 19.5%, N_2 6.1%, the C_{5+} content is 1.4 g/m^3.

The GWC depth of the free gas reservoir no. 1 and no. 2 is 1,755 m bsl, the reservoir rocks are Middle Triassic dolomite

(Hetvehely Dolomite), Lower Cretaceous limestone and Middle Miocene limestone, calcareous sandstone. The combustible part of the natural gas is 75%, the calorific value is 30 MJ/m^3, CH_4 69.3%, CO_2 18%, N_2 6%, the C_{5+} content is 85 g/m^3. The gas contains condensate with a density of 755–762 kg/m^3 (VÖLGYI 1985).

The reservoir no. 3 contains free gas, the GWC depth is 1,990 m bsl. The reservoir rocks are the same as in the free gas reservoirs no. 1 and no. 2. The combustible part of the natural gas is 79%, the calorific value is 30.8 MJ/m^3. The CH_4 content 75.6%, CO_2 17.2%, N_2 3.8%, C_{5+} 40 g/m^3. It contains 23–36 g/m^3 condensate (VÖLGYI 1985).

Geophysical well logs typical for the area are shown on Figure 4.3.11.

Kömpöc. The Köm–4 (1984) and the Köm–6 (1986) wells discovered small free gas reservoirs of low commercial value in the Variscan granite and in the Middle Triassic carbonate basement and in the overlying sediments. No information is available on the composition of the gas.

Kömpöc South (Kömpöc-Dél). The Köm-D–1 well explored a free gas reservoir in the Middle Triassic dolomite (Hetvehely Dolomite) in 1991, with a GWC depth of 3,283 m bsl. The combustible part of the gas is 89.7%, the calorific value is 37.2 MJ/m^3. The CH_4 content is 77.3%, CO_2 9.7%, N_2 0.6%, the C_{5+} content is 56.3 g/m^3.

Mélykút NE (Mélykút-ÉK). The Mé-ÉK–3 well discovered two small dissolved gas containing oil reservoirs in the Middle Triassic fractured limestone (Hetvehely Dolomite) (OWC 1,365 m bsl) and Middle Miocene porous limestone (Ebes/Lajta Fm) (OWC 1,282 m bsl) in 1981. The oil is paraffinic, with a density of 853 and 855 kg/m^3, respectively, containing 60 m^3/m^3 dissolved gas. The combustible part of the lower reservoir is 81.7%, the calorific value is 43.3 MJ/m^3.

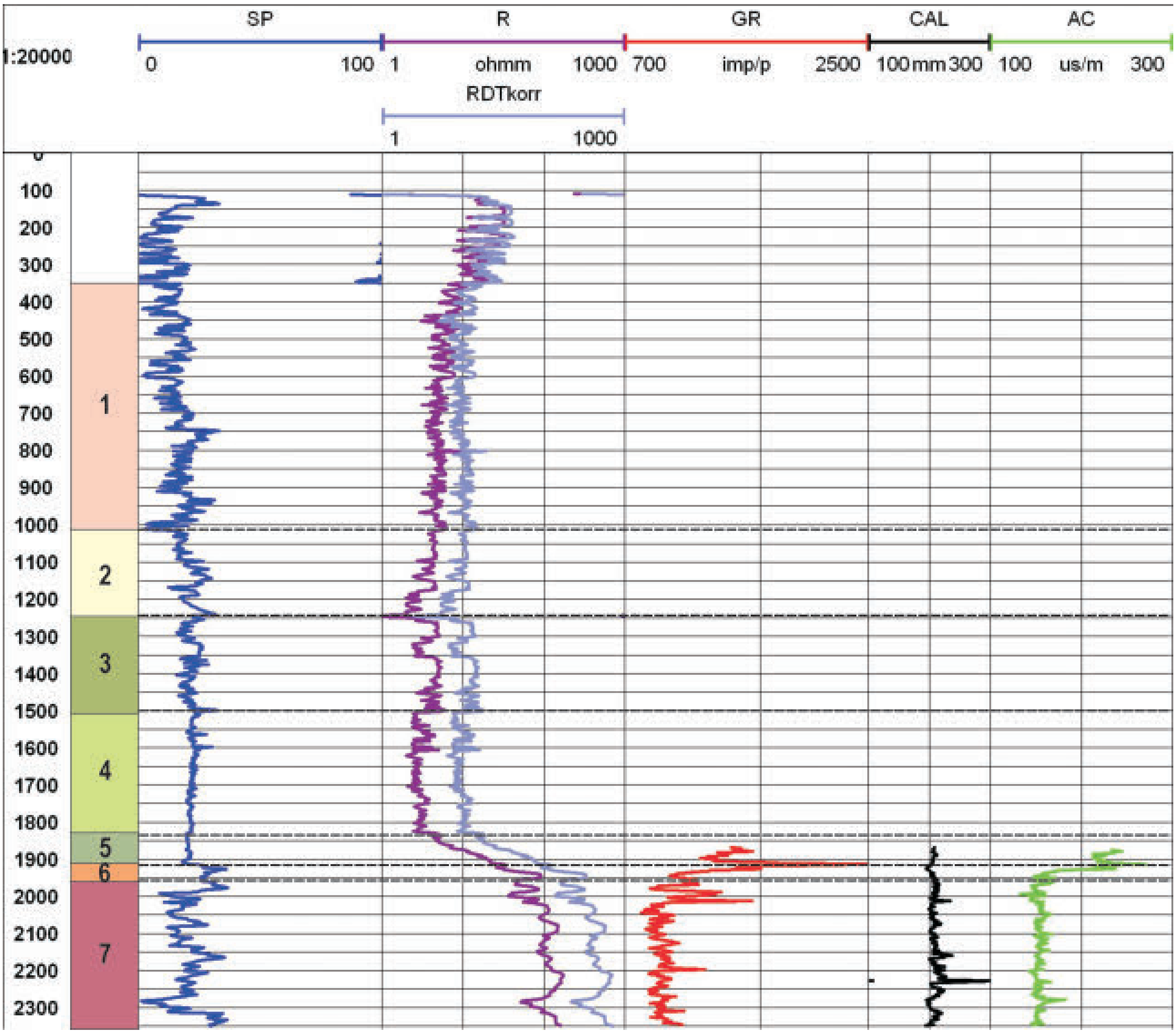


Figure 4.3.11. Geophysical well logs of the Kiskunmajsa Kkm.D–17 well

Legend: SP: spontaneous potential, R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log; AC: acoustic profile. Geological column: 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Szolnok Fm (Lower Pannonian), 4. Endrőd Fm (Lower Pannonian), 5. Endrőd Fm Tótkomlós Calcareous Marl Member (Lower Pannonian), 6. Middle Miocene, 7. Cretaceous, Senonian stage sedimentary basement

The CH_4 content is 62.5%, CO_2 17.8%, N_2 0.5%, C_{5+} content 166 g/m^3. The combustible part of the upper reservoir is 92.5%, the calorific value is 54.2 MJ/m^3. The CH_4 content is 67.1%, CO_2 6.11%, N_2 1.4%, the C_{5+} content is 315 g/m^3.

Öttömös. The Öt–3 well and the Öt–7 well discovered two oil accumulations in Upper Pannonian shaly sandstone in 1969 and 1971, respectively. The lower reservoir has an OWC 909.5 m bsl, and contains naphthenic oil with dissolved gas. The oil density is 888 kg/m^3, the dissolved gas content is 7.8 m^3/m^3, the sulphur content is 0.45%. The combustible part of the dissolved gas is 98.0%, the calorific value is 36.3 MJ/m^3. The CH_4 content is 94.5%, CO_2 0.9%, N_2 1.1%, the C_{5+} content is 0.6 g/m^3. The upper oil reservoir with gas cap has an OWC depth of 859 m bsl. The oil is of the naphthenic type, with a density of 890 kg/m^3, its dissolved gas content is 40 m^3/m^3, the sulphur content 0.45%. The combustible part of the natural gas is 99.0%, the calorific value is 36.8 MJ/m^3. The CH_4 content is 94.6%, CO_2 0.4%, N_2 0.6%, C_{5+} content 2.7 g/m^3.

Öttömös West (Öttömös-Ny). The Öttömös-Ny–I reservoir is known from the Öt-Ny–5 well in 1992. One oil reservoir with gas cap and one free gas reservoir was discovered. The Ött-Ny–I. oil reservoir is in Lower Cretaceous limestone (Nagyharsány Limestone). The depth of the OWC is at 821 m bsl, the density is 931 kg/m^3, and it contains naphthenic oil. The combustible part of the dissolved gas is 93.6%, the calorific value is 33.9 MJ/m^3. The CH_4 content is 92.4%, CO_2 3.2%, N_2 3.2%.

The Öt-Ny–2 well discovered the Öt-Ny–II free gas reservoir. The GWC depth is 784 m bsl. The combustible part of the gas is 94.0%, the calorific value is 34.0 MJ/m^3. The CH_4 content is 93.1%, CO_2 1.5%, N_2 4.5%.

The Öt-Ny–III free gas reservoir was discovered by the Öt-Ny–6 well, the reservoir rock is Middle Triassic Hetvehely Dolomite. The GWC depth is 665 m bsl. The combustible part of the gas is 73.9%, the calorific value is 25.8 MJ/m^3. The CH_4 contents is 72.6%, CO_2 15.4%, N_2 10.7%.

Öttömös East (Öttömös-Kelet). Two separate dissolved gas containing oil reservoirs are known in the field in basement rocks. The Öttömös-Kelet–II dissolved gas containing oil reservoir was discovered by the Ött-K–1 well in 1993. The OWC depth is 895 m bsl. The reservoir rock of the accumulation is Middle Triassic limestone. The oil is paraffinic, its density is 904 kg/m^3, the dissolved gas content is 28 m^3/m^3. The combustible part of the gas is 89.1%, the calorific value is 34.7 MJ/m^3. The CH_4 content is 84.4%, CO_2 9.3%, N_2 1.6%.

The Öttömös-Kelet–I reservoir was found by the discovery well Öt-K–2, drilled in 1992. The OWC depth of the dissolved gas containing oil reservoir is 1,129.5 m bsl. The reservoir rock is Middle Triassic limestone underlying the Jurassic formations (the depth of the pre-Cenozoic basement is merely 630 metres bsl here). The oil is paraffinic, its density is 825 kg/m^3, the dissolved gas content is 16 m^3/m^3, the combustible part of which is 54.0%, the calorific value is 21.1 MJ/m^3. The CH_4 contents is 50.7%, CO_2 41.8%, N_2 4.2%.

Páhi. Two free gas reservoir were discovered by the Páhi–2 well in 2013. Reservoirs are situated in the Upper Pannonian silty sandstone, the depths of the GWC are 646.5, and 723.5 m bsl. The combustible part of the natural gas is 81%, the calorific value is 27.6 MJ/m^3. The CH_4 content is 81%, CO_2 0.1%, N_2 18.8%.

Pálmonostora SW (Pálmonostora-DNy). The occurrence was discovered by the Pálm-DNy–1 well in 1990. One oil reservoir is known in Middle Miocene conglomerate (Abony Formation?). The OWC depth is 2,102 m bsl. The density of the paraffinic oil is 798 kg/m^3, the dissolved gas contents is 85 m^3/m^3. No data is available on the composition of the gas.

Rém. A free gas reservoir was explored by the Ré–4 well in Lower Pannonian sandstone (Szolnok Formation) in 1960. The GWC depth is 146 m bsl. The combustible part of the low amount of gas is 89.5%, the calorific value is 36.4 MJ/m^3.

Soltvadkert. A free gas reservoir has become known in the Lower Pannonian shaly sandstone (Szolnok Formation) by the Sol–1 well in 1964. The OWC depth is at 1,000 m bsl. The combustible part of the gas is 80.4%, the calorific value is 30.3 MJ/m^3. The CH_4 content is 76.6%, CO_2 1.0%, N_2 18.8%.

Soltvadkert East (Soltvadkert-Kelet). A free gas reservoir with condensate in Middle Miocene calcareous sandstone (Ebes/Lajta Fm) was discovered by the Sol-K–1 well in 1982, the GWC depth is 1,015 m bsl. The combustible part of the gas is 74.7%, the calorific value is 30.3 MJ/m^3. The CH_4 content is 70.5%, CO_2 3.3%, N_2 22.1%, C_{5+} content 27.7 g/m^3.

Szank. The discovery well of the field was the Szank Szk–1 in 1964. Multiple oil reservoirs with gas caps have become known under the subconformity of the top Variscan metamorphic rocks and in the overlying Middle Miocene Badenian conglomerate, limestone, calcareous sandstone succession. The OWC depth is 1,815–1,770 m bsl. The densities of paraffinic oil are 817–860 kg/m^3, the sulphur content is 0.5%, the dissolved gas content is 103 m^3/m^3. The combustible part of the dissolved gas is 94.2%, the calorific value is 41.0 MJ/m^3. The CH_4 content is 82.0%, CO_2 1.8%, N_2 4.0%, the condensate content is 52 g/m^3. The combustible part of the cap gas is 96.1%, the calorific value is 43.7 MJ/m^3, CH_4 85.6%, CO_2 1.1%, N_2 2.9%. The density of the condensate in the cap gas is 705 kg/m^3, its quantity is 120 g/m^3 (Völgyi 1985).

After the gas blowout in the Szank–4 well, gas migrated to eight secondary gas reservoir which were formed in the western part of the structure in Upper Pannonian succession under 1,000 metres bsl. The combustible part of the accumulated gas is 96%, the calorific value is 39.6 MJ/m^3, CH_4 86.8%, CO_2 1.6%, N_2 2.4%, condensate content 20 g/m^3 (Völgyi 1985).

Two additional oil reservoirs were successfully discovered by the Szk–116 and –118 well in 1976. The reservoir rock of the SzkNy–I oil reservoir with gas cap is Middle Miocene Badenian calcareous sandstone and conglomerate, the OWC depth is 1,783.5 m bsl. The oil is of paraffinic-intermediate type, density is 856 kg/m^3, sulphur content 0.46%, dissolved gas

content 104 m^3/m^3. The combustible part of the cap gas is 95.7%, the calorific value is 39.1 MJ/m^3. CH_4 content 84.6%, CO_2 2.0%, N_2 2.3%, C_{5+} 30 g/m^3. The SzkNy–II oil reservoir OWC depth is 1,808 m bsl, the reservoir rock is coarse clastic sediment. The oil is paraffinic-intermediate, its density is 850 kg/m^3, the sulphur content is 0.38%. There is little dissolved gas content.

Szank West (Szank-Nyugat). A natural gas reservoir was discovered by the Szk–14 well in 1966, and later, by the Szk-Ny–2 (1978), Szk-Ny–10 (1981) and Szk–123 (1977) wells. A total of 8 natural gas and 4 oil reservoirs have become known. Five of the free gas reservoirs are situated at a depth near 2,010 m bsl (GWC), in Middle Miocene Badenian calcareous marl. The combustible part of the accumulated gas is 83.1%, the calorific value is 39.9 MJ/m^3. The CH_4 content is 83.9%, CO_2 2.1%, N_2 4.8%, C_{5+} 78.1 g/m^3. Two free gas reservoirs are situated in a depth of 1,955 m bsl (GWC) in Badenian silty sandstone. The combustible part of the gas is 94.5%, the calorific value is 38.7 MJ/m^3. CH_4 content 87.4%, CO_2 1.1%, N_2 4.4%, the C_{5+} content 53 g/m^3.

The Szk-Ny–4 well discovered an oil reservoir at a depth of 1,890 m bsl (OWC) in Badenian calcareous marl. The density of the paraffinic is 883 kg/m^3. The Szk-Ny–5 well discovered an oil reservoir with gas cap (OWC is 1,870 m bsl), above it one free gas reservoir has become known separately. The reservoir rock is Badenian calcareous marl, breccia. The oil is paraffinic, its density is 842 kg/m^3. The combustible part of the cap gas is 94.3%, the calorific value is 39.5 MJ/m^3, the CH_4 content 85.4%, CO_2 1.9%, N_2 3.8%, C_{5+} 62 g/m^3. The gas contains 190 g/m^3 condensate with a density of 738 kg/m^3 (VÖLGYI 1985). The combustible part of the gas accumulated in the free gas reservoir is 94.2%, the calorific value is 39.3 MJ/m^3, CH_4 85.7%, CO_2 1.2%, N_2 4.6%, C_{5+} 55 g/m^3.

The oil reservoir of the Szk-Ny–10 well is in Badenian limestone, the OWC depth is 1,861 m bsl. The density of the paraffinic oil is 880 kg/m^3, and does not contain dissolved gas. The oil reservoir of the Szk–123 well is in Badenian shaly sandstone (OWC 1,870 m bsl), is of the intermediate type, and stores oil with a density of 900 kg/m^3.

Szank NE (Szank-ÉNy). The Szk-ÉNy–1 well discovered an oil reservoir with dissolved gas in 1977 in Lower–Middle Jurassic, fractured marl–limestone succession, in an OWC depth of 1,675 m bsl. The density of paraffinic oil density is 852 kg/m^3, the sulphur content is 0.18%, the dissolved gas content is 2.3 m^3/m^3. The combustible part of the gas is 89.3%, the calorific value is 39.8 MJ/m^3, CH_4 76.4%, CO_2 7.4%, N_2 3.3%, C_{5+} 50 g/m^3.

Tázlár. The occurrence was discovered by the Táz–1 well in 1966. Two free gas and three oil reservoirs are known in the field. The OWC depth of the dissolved gas containing oil reservoir no. 2 is 2,100 m bsl. The oil is accumulated in the fractured top of the Variscan metamorphic basement rocks. The density of the paraffinic–intermediate oil is 914 kg/m^3, the dissolved gas content is 35 m^3/m^3. The combustible part of the gas is 75.8%, the calorific value is 31.4 MJ/kg, CH_4 68.6%, CO_2 18.2%, N_2 6.0%, the C_{5+} content is 20 g/m^3.

The reservoir rock of the oil reservoir no. 1 is Middle Miocene conglomerate and sandstone. The OWC depth is 2,020 m bsl. The density of the intermediate type oil is 906 kg/m^3, the dissolved gas content is 35 m^3/m^3. The combustible part of the gas is 70%, CH_4 64.0%, CO_2 21.5%, N_2 8.6%, C_{5+} 20 g/m^3.

The depth of the multiple oil reservoir with gas cap no. 1 is at 1,940 m bsl, the reservoir rock is Middle Miocene limestone and coarse clastic rock, and the underlying Variscan metamorphic rocks in the pre-Cenozoic basement. The oil is paraffinic–intermediate, its density is 909 kg/m^3, the dissolved gas content is 55 m^3/m^3, the combustible part is 68.8%, the calorific value is 28.6 MJ/kg. The CH_4 content is 63.2%, CO_2 22.6%, N_2 8.6%, the C_{5+} content is 44 g/m^3. The combustible part of the cap gas is 68.7%, the CH_4 content is 63.3%, CO_2 22.6%, N_2 8.6%, C_{5+} 57 g/m^3. The density of the condensate is 754 kg/m^3, the amount is 50–55 g/m^3.

The GWC depth of the lower of the two free gas reservoir is 1,348 m bsl, the gas is situated in Lower Pannonian sandstone. The combustible part is 95.6%, the calorific value is 38.8 MJ/kg. The CH_4 content is 88.5%, CO_2 0.8%, N_2 3.6%, the C_{5+} content is 34 g/m^3. The density of the condensate is 714 kg/m^3, the amount is 58 g/m^3. The upper free gas reservoir is located at a depth of 1,322 m bsl in Lower Pannonian shaly sandstone, the combustible part of the gas is 95.0%, the calorific value is 35.3 MJ/kg. CH_4 92.9%, CO_2 0.5%, N_2 4.5%, the C_{5+} content is 22 g/m^3. The condensate quantity is 20 g/m^3.

Tázlár North (Tázlár Észak). An oil reservoir with dissolved gas was discovered by the Táz-É–2 well in 1985 at a depth of 2,173 m bsl (OWC) in the Early Palaeozoic, fractured metamorphic basement with a low amount of free gas reservoir above it in the Middle Miocene conglomerate. The density of the paraffinic oil is 882 kg/m^3, the dissolved gas content is 15.2 m^3/m^3. The combustible part of the gas is 96.3%, the calorific value is 41.0 MJ/m^3. The CH_4 content is 79.9%, CO_2 0.6%, N_2 3.1%, C_{5+} 27.5 g/m^3. The free gas reservoir GWC depth is 1,983.5 m bsl, the combustible part is 93.2%, the calorific value is 35.4 MJ/m^3, CH_4 86.4%, CO_2 2.5%, N_2 4.3%, the C_{5+} content is 40.3 g/m^3.

A free gas reservoir was discovered by the Táz-North–6 well drilled near the well above at a depth of 2,048 m bsl (GWC) in 1985. The combustible part of the gas is 93.1%, the calorific value is 39.4 MJ/m^3, CH_4 83.9%, CO_2 2.1%, N_2 4.0%, the C_{5+} content is 122.3 g/m^3.

The Táz-É–9 well was drilled to the south-east of the two wells referred to above and discovered a dissolved gas containing oil reservoir at a depth of 2,260 m bsl (OWC). The reservoir rock is Variscan granite, amphibolite. The density of the paraffinic-intermediate oil is 858.2 kg/m^3, the dissolved gas contents is 70.8 m^3/m^3, CH_4 74.1%, CO_2 6.2%, N_2 2.2%, the C_{5+} content is 44.5 g/m^3.

Tompa. The Tp–5 well explored a small free gas reservoir in 1959 at a depth of 1,900 m bsl (GWC) in Lower Pannonian sandstone. The combustible part of the gas is 75.8%, the calorific value is 28.2 MJ/m^3, it contains 23.9% nitrogen gas.

Tompa North (Tompa-Észak). The oil reservoir formed in Cretaceous limestone, calcareous marl, marl was discovered by the Tp-É–1 well in 1982. The OWC depth is in 533 m bsl. The density of the presumably biodegraded oil is 959.3 kg/m^3, there is no dissolved gas content, the CH_4 content is 1.4%, CO_2 98.4%, N_2 1.9%.

Zsana North (Zsana-Észak). The natural gas field with a small sized oil reservoir was explored by the Zsana-É–2 well in 1978. The reservoir rock is Middle Miocene Badenian lithothamnium limestone, forming a combined reservoir with Triassic dolomite and sandstone. The combustible part of the natural gas is 87.5%, the calorific value is 34.9 MJ/m^3. The CH_4 content is 82.0%, CO_2 8.4%, N_2 4.1%, C_{5+} 39.8 g/m^3. The amount of the condensate with a density of 731–760 g/m^3 is 40–45 g/m^3. The oil reservoir was discovered by the Zsana-É–14 well (OWC 1,798 m bsl) has an oil of the paraffinic-intermediate type, its density is 851.7 kg/m^3, sulphur content 0.1%, dissolved gas contents 120.4 m^3/m^3. The free gas reservoir is utilised as underground gas storage.

Zsana West (Zsana-Nyugat). Two geographically separated free gas reservoir constitute this field. The Zsana-Ny–1 well discovered an occurrence in 1988, the reservoir rock is Lower Cretaceous limestone. The combustible part of the natural gas is 88.9%, the calorific value is 32.9 MJ/m^3. The CH_4 content is 86.6%, CO_2 4.9%, N_2 6.2%, C_{5+} 6.1 g/m^3. The free gas reservoir of the Zsana-Ny–2 well has become known in 1989. The reservoir rock is Lower Triassic limestone and conglomerate. The combustible part of the gas is 89.5%, the calorific value is 34.9 MJ/m^3, CH_4 content: 84.7%, CO_2 4.4%, N_2 6.2%, the C_{5+} content is 19.8 g/m^3.

Szeged-Basin

Algyő. In terms of its original in-place oil and natural gas resources this field is the most significant occurrence in Hungary. The Algyő–1 well's drilling was planned in 1965 as an exploration well, based on gravity and seismic measures. However, the oil and natural gas accumulated in the deep became known from the unexpected blowout of the water exploration wellbore Tápé–1, drilled somewhat earlier the same year. By now, more than a thousand exploration, production, infill and water injection wells have been drilled there.

A number of reservoirs have become known in structural and stratigraphic traps formed on the top of Variscan metamorphic basement combined with faults, and in the overlying Neogene pseudoanticline structure. Discovered reservoirs can be classified into reservoir groups according to stratigraphic horizons. The reservoir of the "Deszk horizon" was formed in the metamorphic basement and the overlying Upper Miocene "Lower Pannonian" basal conglomerate.

A total of 45 reservoirs differentiated by numbers are identified in the pseudoanticline, in the slightly dipping beds of delta slope origin of Lower Pannonian sandstones. The 25 reservoirs formed in the Upper Pannonian sandstone are classified in reservoir groups using various names from bottom to top, such as the Maros, Algyő, Szeged, Szőreg, Csongrád and Tisza horizons (Figure 4.3.12).

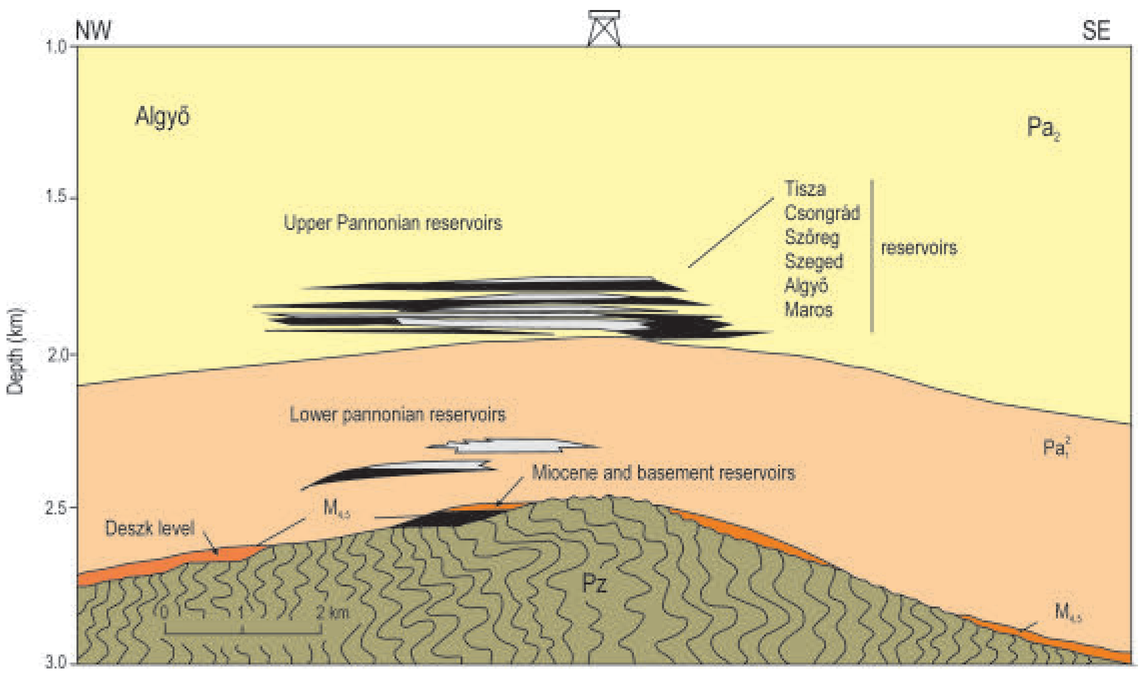


Figure 4.3.12. Positions of the crude oil and natural gas reservoirs in the Algyő field (according to DANK 1988)

In the *Deszk horizon,* an oil reservoir with a gas cap is known, the OWC depth of which is 2,480 m bsl. The oil is paraffinic, its density is 820 kg/m^3, the dissolved gas content is 180 m^3/m^3. The combustible part of the cap gas is 95.0%, the calorific value is 42.1 MJ/m^3. The gas CH_4 content is 83.2%, the CO_2 content is 4.3%, the N_2 is 0.3%, the C_{5+} content is 0.4 g/m^3.

Reservoirs of the Lower Pannonian (AP) succession are as follows:

Oil reservoirs. Reservoirs numbered AP–7/7 – AP–17 are located in a OWC depth range of 2,044.5–2,535 m bsl. Nine oil reservoirs are known here in silty sandstone, three of them with dissolved gases and six with gas caps. The oils are mainly paraffinic, to a lesser extent of intermediate type, their density varies in a range of 780 and 880 kg/m^3, and the general trend is that density values decrease as the depth declines. The sulphur content of the oils is 0.2–0.3%, the dissolved gas content is between 69–185 m^3/m^3. The combustible part of the dissolved and cap gases is 96.0–97.9%, the calorific value is 38.4–46.0 MJ/m^3. The CH_4 content is 83.7– 91.3%, CO_2 1.1–3.1, N_2 0.7–0.9%, C_{5+} 46–137 g/m^3.

Free gas reservoirs. The 36 reservoirs with numbering from AP–4/2 to AP–18 are known at a GWC depth between 1,894 and 2,548 m bsl. Their reservoir rock is silty sandstone, sandstone. The combustible part of the natural gas is 90.2–98.6%, the calorific value is 38.3–46.0 MJ/m^3. The CH_4 content is 74.8–91.2%, CO_2 0.9–5.1%, N_2 0.4–6.3%, the C_{5+} content is 55–130 g/m^3.

The *reservoirs of the Upper Pannonian succession* are as follows:

One oil reservoir and seven free gas reservoirs are known in the *Maros horizon*. The oil reservoir is situated in shaly sandstone, the OWC depth is 2,146.5 m bsl. The density of paraffinic oil is 806 kg/m^3, the sulphur content is 0.02–0.5%, the dissolved gas content is 69 m^3/m^3. The combustible part of the cap gas is 97.7%, the calorific value is 44.1 MJ/m^3, CH_4 88.1%, CO_2 1.6%, N_2 0.7%, the C_{5+} content is 46 g/m^3. The reservoir rock of the free gas accumulations in the Maros horizon is silty sandstone, the GWC depth is in a range of 1,903–2,091 m bsl. The combustible part of the gases is 96.7–98.0%, the calorific value is 39.6–40.3 MJ/m^3. The CH_4 content is 77.6–89.4%, CO_2 1.0–1.5%, N_2 0.6–2.0%, the C_{5+} content is 72–107 g/m^3.

Two oil reservoirs with gas caps have become known in silty sandstone in the *Algyő horizon*, at an OWC depth of 1,875 and 1,880 m bsl. The density of the paraffinic oil is 830 and 840 kg/m^3, the sulphur content 0.18 and 0.25%, the dissolved gas content is 86.0 and 86.8 m^3/m^3. The combustible part of the cap gas is 98%, the calorific value is 37.7 and 41.4 MJ/m^3, CH_4 89.8 and 90.1%, CO_2 0.7 and 0.9%, N_2 1.4 and 1.3%, C_{5+} 155 and 118 g/m^3.

Three oil reservoirs with gas cap are distinguished in the *Szeged horizon* in silty sandstone. The OWC depth of the reservoirs are 1,813, 1,840 and 1,855 m bsl. The density of paraffinic oil is 800–820 kg/m^3, the sulphur content is 0.05–0.5%, the dissolved gas content is 105–112 m^3/m^3. The combustible part of the cap gas is about 98%, the calorific value is 40.5–42.2 MJ/m^3, CH_4 88.1–88.9%, CO_2 0.5–0.11%, N_2 0.9 and 1.4%, C_{5+} 111–117 g/m^3.

In the *Szőreg horizon* the Szőreg–1 oil reservoir with gas cap (1,770 m OWC) and the Szőreg–2 free gas reservoir (1,147 m GWC) are known in silty sandstone. The oil reservoir is paraffinic–intermediate type, its density is 800 kg/m^3. The combustible part of the cap gas is 98.4%, the calorific value is 43.4 MJ/m^3, CH_4 87.0%, CO_2 0.9%, N_2 0.7%. The combustible part of the free gas reservoir is 98.5%, the calorific value is 41.2 MJ/m^3, CH_4 content 85.2%, CO_2 0.8%, N_2 0.7%, C_{5+} 179 g/m^3.

In the *Csongrád horizon* the Csongrád North reservoir group includes four natural gas reservoir (GWC 1,683–1,719 m bsl), and in the Csongrád South reservoir group there are three oil reservoirs with gas caps (OWC 1,657–1,696) in sandstone reservoir rocks. The combustible part of the gas in the natural gas reservoirs is 97.0–98.6%, the calorific value is 41.9–42.3 MJ/m^3, CH_4 84.9–86.8%, CO_2 0.5%, N_2 1.0%, C_{5+} 45–194 g/m^3. The density of the paraffinic oil is 771–800 kg/m^3, the sulphur content is 0.4–0.5%, the dissolved gas content is 113–204 m^3/m^3. The combustible part of the cap gas is 96.7–98.6%, the calorific value is 46.4–47.2 MJ/m^3, CH_4 88.1– 88.9%, CO_2 1.0–1.1%, N_2 1.5–2.1%, C_{5+} 51–138 g/m^3.

In the three reservoirs of the *Tisza horizon* undersaturated oil accumulated in sandstone and silty sandstone at an OWC depth between 1,621.5 and 1,650 m bsl. The oil is of the paraffinic type, the sulphur content is 0.02–0.12%, the dissolved gas content is 108–720 m^3/m^3. The combustible part of the gas is 96.2–98.3%, the calorific value is 54.1–60.4 MJ/m^3, CH_4 49.2–76.1%, CO_2 0.5–1.2%, N_2 0.9–2.6%, C_{5+} 197 g/m^3.

Five overmigrated free gas reservoirs are also recorded in the depth range of 80.9–1,015 metres bsl with small sized resources. Gases of those reservoirs derived from lower level accumulations escaped across holed wells.

Ásotthalom. The Ás–2 discovery well of the oil occurrence was drilled in 1967. An *undersaturated oil reservoir* was explored in the Variscan metamorphic basement and in the overlying Middle Miocene Sarmatian conglomerate and sandstone beds ("*Bácska horizon*"). The Ás–3 well discovered also a separated *free gas reservoir* in a lithologic trap to the southwest from the oil accumulation in Lower Pannonian sandstone. The OWC depth of the oil reservoir is 975 m bsl. The density of the intermediate type oil is 856 kg/m^3, the dissolved gas content 36.7 m^3/m^3, sulphur content 0.36%, combustible part of the dissolved gas is 91%, calorific value 41.7 MJ/m^3, CH_4 75.5%, CO_2 5.6%, N_2 4.1%, C_{5+} 108.9 g/m^3. The GWC of the free gas reservoir is 769 m bsl, the combustible part of the natural is 93.4%, the calorific value is 34.8 MJ/m^3, CH_4 content 90.3%, CO_2 0.4%, N_2 6.2%.

Ásotthalom North (Ásotthalom-Észak). The Ás-É–2 well drilled 1985 discovered an *oil reservoir with gas cap* in the

Variscan metamorphic basement and the overlying Middle Miocene clastic beds, in an OWC depth of 1,983 m bsl. The density of the intermediate type oil is 886.3 kg/m^3, dissolved gas content 54.5 m^3/m^3, sulphur content 0.01%. The combustible part of the dissolved gas is 33.6%, the calorific value is 17.4 MJ/m^3, CH_4 content 24.6%, CO_2 65.0%, N_2 1.4%, C_{5+} 44 g/m^3.

Dorozsma. The Dorozsma–2 exploration well was drilled in 1965, and discovered *two oil reservoirs*. Additional wells explored further oil reservoirs. The "*Dorozsma deep*" reservoir contains undersaturated oil found in a structural trap of the Variscan basin basement metamorphites and in the overlying Middle Miocene breccia, with an OWC depth of 2,950 m bsl. The density of the paraffinic oil is 809 kg/m^3. The dissolved gas content is 163 m^3/m^3, sulphur content 0.1%, combustible part of the dissolved gas 95.6%, calorific value 37.1 MJ/m^3, CH_4 content 42.7%, CO_2 1.8%, N_2 2.6%, C_{5+} 68 g/m^3.

The Do–10 well explored *two oil reservoirs* in 1982 in the northern part of the field. One oil reservoir is known *in Middle Miocene conglomerate* in an OWC depth of 2,760 m bsl. The density of the accumulated intermediate type oil is 882 kg/m^3, the dissolved gas content is 80 m^3/m^3, the combustible part of the dissolved gas is 90.0%, the calorific value is 50.5 MJ/m^3, CH_4 61.6%, CO_2 8.0%, N_2 0.02%, the C_{5+} 106 g/m^3. One undersaturated oil reservoir was formed in the base *Lower Pannonian calcareous marl* at an OWC depth of 2,630 m bsl. The density of the paraffinic type oil is 823.6 kg/m^3. The dissolved gas content is 60 m^3/m^3, combustible part of the dissolved gas 93%, calorific value 41 MJ/m^3, no data is available on the composition of the gas.

The Szeged-É (Szeged North) (Do–6 well, 1973), Szeged-D (Szeged South) (Do–2 well) and Szőreg–1 (Do–6 well) *undersaturated oil reservoirs* are known in Upper Pannonian silty sandstone. The OWC of the Szeged-D reservoir is at 1,548.5 m bsl, the density of the paraffinic oil is 834 kg/m^3, the dissolved gas content is 101 m^3/m^3, the combustible part of the dissolved gas is 96.2%, calorific value 45.3 MJ/m^3, CH_4 76.1%, CO_2 2.3%, N_2 1.5%, C_{5+} 39 g/m^3. The depth of the Szeged-É reservoir is 1,535 m bsl, it contains paraffinic oil of 845 kg/m^{3}density.The dissolved gas contain is 101 m^3/m^3,the combustible part of the dissolved gas is 93%, the calorific value is 41.5 MJ/m^3, CH_4 75.0%, CO_2 2.5%, N_2 2.0%. The OWC depth of the Szőreg–1 reservoir is 1,481.5 m bsl, the density of the paraffinic–intermediate type oil is 834.3 kg/m^3, dissolved gas content 102 m^3/m^3, combustible part of the dissolved gas 95.5%, calorific value 45.5 MJ/m^3, CH_4 75%, CO_2 2.5%, N_2 2.0%.

Dorozsma–Szentmihálytelek. Two free gas reservoirs by the Kiskundorozsma Do–28 well (1989), one undersaturated oil reservoir by the Do–29 well (1988) and also one undersaturated oil reservoir by the Szentmihálytelek Szmt–1 well (2000) were discovered.

The lower free gas reservoir of Do–28 well is at 2,721.5 m bsl GWC depth in Middle Miocene sandstone. The combustible part of the gas is 91.2%, the calorific value 40.2 MJ/m^3, CH_4 76.6%, CO_2 1.0%, N_2 1.7%, C_{5+} 43 g/m^3. The combustible part of the gas in the upper reservoir at 2,692 m bsl GWC depth is 91.5%, the calorific value 39.2 MJ/m^3, CH_4 78.5%, CO_2 6.8%, N_2 1.7%, C_{5+} 32 g/m^3.

In the Do–29 well the OWC depth of the oil reservoir is 2,735 m bsl in Lower Pannonian silty sandstone. The density of the intermediate type oil is 874 kg/m^3. The dissolved gas content is 40 m^3/m^3, no data are available for its calorific value and composition.

In the Szmt–1 well undersaturated oil reservoir is known at an OWC depth of 2,938.5 m bsl in structural trap in the Variscan metamorphic basement and in the overlying Lower Pannonian conglomerate. The oil is of the paraffinic type, dissolved gas content 250 m^3/m^3, combustible part 88.3%, calorific value 40.1 MJ/m^3, CH_4 72.9%, CO_2 7.8%, N_2 3.4%, C_{5+} 51 g/m^3.

Ferencszállás. The oil and gas occurrence is situated to south–south-west from the Algyő field on the Algyő basement high ridge. The discovery well was the Ferencszállás F–3, drilled in 1969. A total of 25 reservoirs were distinguished in the field, one of which is a natural gas deposit directly in the basal conglomerate overlain the pre-Cenozoic basin basement ("*Deszk horizon*"), 16 oil and natural gas deposits are in Lower Pannonian sandstones, 8 natural gas reservoirs in Upper Pannonian sandstones. Typical trap forms of the field is the stratigraphic trap developed along the surface of the metamorphic basement and the structural/lithologic traps in the Neogene pseudoanticline above the basement.

Stratigraphically the lowest reservoir in the centre of the occurrence is the *Deszk horizon*. The GWC depth of the free gas reservoir is at 2,268 m bsl. The reservoir rock is Lower Pannonian conglomerate (Békés Conglomerate Fm) overlying the Variscan metamorphic basement. Conglomerate beds are missing from the top of the basement high, it was eroded away. The combustible part of the accumulated gas is 91.0%, the calorific value 36.4 MJ/m^3, CH_4 83.2%, CO_2 7.0%, N_2 1.9%, C_{5+} 17 g/m^3.

Reservoirs explored *in the Lower Pannonian sequence* — stratigraphically in the succession above the Deszk horizon — are as follows from the bottom to up:

Pl1–11 and Pl1–11-II undersaturated oil reservoirs. Their OWC depth is 2,339 and 2,338 m bsl, respectively. The reservoir rock is clay-bearing sandstone. The density of the paraffinic type oil is 780 and 815 kg/m^3, sulphur content 0.15%, dissolved gas content 180 m^3/m^3, combustible part 95.0% and 94.6%, calorific value 39.6% and 40.0 MJ/m^3, CH_4 83.8% and 81.2%, CO_2 3.9 and 4.6%, N_2 1.0 and 0.8%, C_{5+} 33 g/m^3.

Pl1–9–10 a free gas reservoir. The GWC depth is 2,337 m bsl. The combustible part of the gas is 95.1%, the calorific value is 40.6 MJ/m^3, CH_4 content 83.8%, CO_2 3.9%, N_2 0.9%, C_{5+} 39 g/m^3.

Pl1–8/2–3 oil reservoir with gas cap. The OWC depth is 2,262 m bsl, the reservoir rock is silty sandstone. The density of the paraffinic type oil is 807 kg/m^3, the sulphur content is 0.15%, dissolved gas content 133 m^3/m^3, combustible part of the dissolved gas 95.3%, calorific value 39.5 MJ/m^3, CH_4 86.3%, CO_2 3.2%, N_2 0.9%, C_{5+} 0.6 g/m^3.

Pl1–7/1–2K and –7/1–2Ny oil reservoirs with gas caps in silty sandstone, their OWC depth is 2,235 and 2,256 m bsl, respectively. The density of the paraffinic oil is 820 and 817 kg/m^3, sulphur content 0.15%, dissolved gas content 133 m^3/m^3, the combustible part of the dissolved gas 95.0%, the calorific value 40.2 MJ/m^3, CH_4 85.1%, CO_2 3.2%, N_2 1.8%, C_{5+} 45 g/m^3.

Pl1–6/4–I, –6/4–II, –6/1–3 and –5/5 free gas reservoirs in silty sandstone. The GWC depth is 2,232, 2,205, 2,180 and 2,174 m bsl, respectively. The combustible part of the gas is 95.6–96.6%, the calorific value 40.6–40.9 MJ/m^3, CH_4 85.1–88.2%, CO_2 3.0–3.8%, N_2 1.1–1.2%, C_{5+} 45–49 g/m^3.

Pl1–5/3–4D, –5/3–4K, –5/3–4ÉNy, –5/1–2K–I and –5/1–2K–II oil reservoirs. The 5/3–4K reservoir has no gas cap. Their respective OWC depth is between 2,155–2,134 m bsl, the reservoir rock is clay-bearing sandstone. The type of the oils is paraffinic, the density is 820 kg/m^3, sulphur content 0.15%, dissolved gas content 127–132 m^3/m^3, the combustible part of the dissolved gas is 95.7–96.4%, the calorific value is 42.2–44.0 MJ/m^3. The CH_4 content is 76.4–81.5%, CO_2 2.9–3.5%, N_2 0.8–1.2%, the C_{5+} 41–45 g/m^3.

Pl1–5/1–2ÉNy free gas reservoir. The GWC depth is 2,124 m bsl. The reservoir rock is clay-bearing sandstone. The combustible part of the gas is 95.8%, the calorific value is 41.8 MJ/m^3, CH_4 content 81.2%, CO_2 2.9%, N_2 1.2%, C_{5+} 44 g/m^3.

Reservoirs in the Upper Pannonian sequence:

Eight *free gas reservoirs (Pl2–1–8)* are known in Upper Pannonian silty/shaly sandstone in a GWC depth of 1,280 and 1,648 m. The combustible part of the natural gas is 96.1–97.4%, the calorific value is 42.7–53.8 MJ/m^3, CH_4 66.5–86.5%, CO_2 0.8–1.7%, N_2 1.6–3.3%, C_{5+} 44–131 g/m^3.

Figure 4.3.13 shows geophysical well logs typical for the area.

Ferencszállás East–Kiszombor (Ferencszállás-K–Kiszombor). One oil reservoir with gas cap and three free gas reservoirs are known in the field found on the Algyő basement high to the south-east from the Ferencszállás field. A lesser part of the occurrence extends over the national border. The discovery wells are the FK–1 and the Zomb–1, which were drilled in 1973. Trap types are stratigraphic in the case of the basement reservoir and lithologic in the overlying beds. The reservoir rock of the lowest, so-called *Zombor reservoir* is the Variscan metamorphite of the basement and the unconformably overlying Lower Pannonian conglomerate. The OWC depth is 2,220 m bsl. The density of the accumulated paraffinic oil is 820 kg/m^3, sulphur content 0.16%, dissolved gas content 113 m^3/m^3, the combustible part of the dissolved gas is 95.5%, the calorific value is 40.1 MJ/m^3. The CH_4 is 84.9%, CO_2 4.0%, N_2 0.5%, C_{5+} 28 g/m^3.

Two *free gas reservoirs (Pl1–5/1–2 and –3–4)* are known in *Lower Pannonian* clay-bearing sandstone reservoir rock, in a GWC depth of 2,144 m bsl. The combustible part of the gas is 95.7%, the calorific value is 39.1 MJ/m^3, CH_4 83.8 and 82.1%, CO_2 2.9%, N_2 1.4%, C_{5+} 170 g/m^3.

The *free gas reservoir Pl2–5* is known in the *Upper Pannonian* clay-bearing sandstone reservoir rock in a GWC depth of 1,664 m bsl. The combustible part of the gas is 95.9%, the calorific value is 39.1 MJ/m^3, CH_4 83.1%, CO_2 1.1%, N_2 3.0%.

Forráskút–Sándorfalva. Four horizontally separated accumulations can be found in the field. The single *T1–EK natural gas reservoir* was discovered by the Sándorfalva S–I well in 1974. Its GWC depth is 3,739 m bsl, the reservoir rock is Lower Triassic sandstone and siliceous shale unconformably overlying the Variscan basement. The natural gas was accumulated in a stratigraphic trap, the combustible part is 82.3%, the calorific value is 30.0 MJ/m^3, CH_4 81.4%, CO_2 17.4%, N_2 0.3%, C_{5+} 2 g/m^3.

The Forráskút F.kút–3 (1977), –4 (1978), –7 (1981) wells explored an occurrence consisting of one oil reservoir with gas cap and four free gas reservoirs. The GWC depth of the *free gas reservoir* named *T2–M–III/1* is 3,121 m bsl, it is in a structural trap in Middle Triassic dolomite breccia and in the overlying Middle Miocene Badenian sandstone. The combustible part of the gas is 74.0%, the calorific value is 27.7 MJ/m^3, CH_4 71.5%, CO_2 24.2%, N_2 1.7%, the C_{5+} 8 g/m^3. The *free gas reservoir M–III/1K* (2,900 m bsl GWC), *M–II/3* (2,987 m), and *M–III/1–Ny* (3,032 m) are known in Middle Miocene Badenian conglomerate in a structural trap. The combustible part of the gases are 94.4, 91.5 and 92.1%, calorific value 34.1, 33.1 and 41.0 MJ/m^3, CH_4 93.7, 90.1 and 80.8%, CO_2 4.3, 5.3 and 6.1%, N_2 1.3, 3.2 and 1.8%, C_{5+} 2.0, 0.3 and 103 g/m^3. The *M–Pl1–E oil reservoir with gas cap* is situated in Lower Pannonian calcareous marl in a structural trap, in an OWC depth of 2,830 m bsl. The oil is of an intermediate type, its density is 863 kg/m^3, dissolved gas contents 100 m^3/m^3. The combustible part of the cap gas is 94.5%, the calorific value is 33.5 MJ/m^3. The CH_4 content is 94.4%, CO_2 4.2%, N_2 1.4%.

The F.kút–5 (1978) and F.kút–8 (1981) wells discovered one oil and two free gas reservoirs. The *lower* of the two *free gas reservoirs* is at a GWC depth of 3,333 m bsl, the gas is accumulated in the fractures of the lithologically closed Variscan metamorphic basement. The combustible part of the gas is 95.1%, the calorific value is 35.5 MJ/m^3, CH_4 92.3%, CO_2 4.7%, N_2 0.2%, C_{5+} content 9 g/m^3. The *upper free gas reservoir T1–D* (3,302 m bsl GWC) is closed by facies change, the reservoir rock is Lower Triassic conglomerate. The combustible part of the gas is 94.8%, the calorific value is 35.9 MJ/m^3, CH_4 91.6%, CO_2 4.7%, N_2 0.5%, C_{5+} 16 g/m^3. The *M–Pl1–D undersaturated oil reservoir* is closed by facies change, the reservoir is Lower Pannonian calcareous marl. The density of the intermediate type oil is 854 kg/m^3, the dissolved gas content is 100

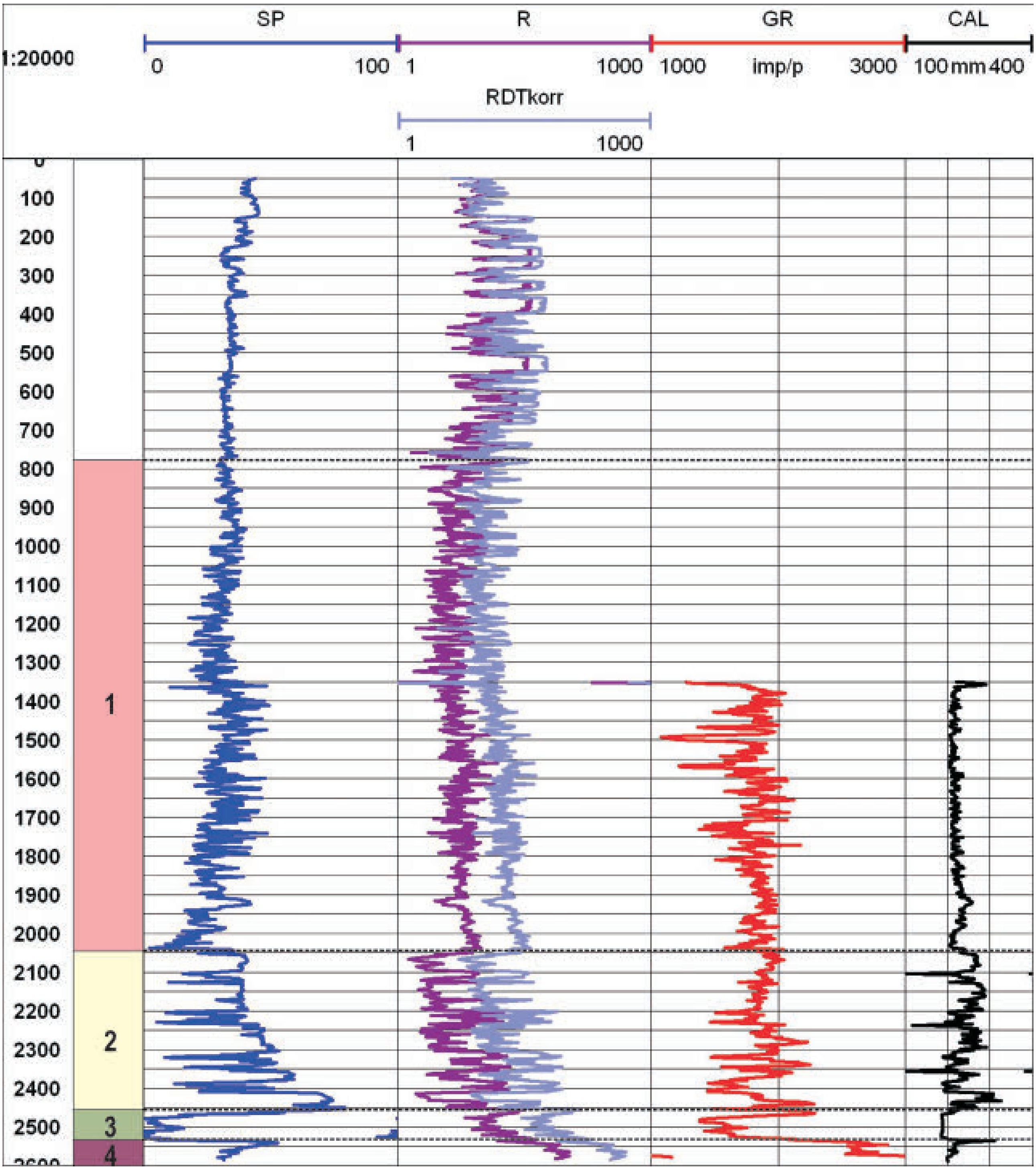


Figure 4.3.13. Geophysical well logs of the Ferencszállás F–10 well

Legend: SP: spontaneous potential, R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log. Geological column: 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Endrőd Fm, Tótkomlós Calcareous Marl Member (Lower Pannonian), 4. Variscan bottom

m^3/m^3. The combustible part of the dissolved gas is 99.5%, the calorific value is 38.8 MJ/m^3, CH_4 92.6%, CO_2 0.1%, N_2 0.4%, the C_{5+} content 6 g/m^3.

The F.kút–11 well discovered *undersaturated oil reservoir (M–Pl1–Ny)* in 1984 in Lower Pannonian calcareous marl closed by facies change (2,468 m bsl OWC). The density of the intermediate type oil is 855 kg/m^3, the dissolved gas content is 100 m^3/m^3. The combustible part of the dissolved gas is 97.1%, the calorific value is 40.1 MJ/m^3, CH_4 85.1%, CO_2 1.0%, N_2 2.9%, C_{5+} 20 g/m^3.

Kelebia North (Kelebia-Észak). The Kel–1 (1968) and the Kel–5 (1970) wells discovered *two* horizontally separated *undersaturated oil reservoirs*. Both reservoirs are in structurally closed stratigraphic traps, in the basement Variscian metamorphites and in the overlying Middle Miocene Sarmatian stage calcareous sandstone and limestone ("*Bácska horizon*"). Their OWC depth is 949 and 993 m bsl, respectively. The accumulated oils are of the intermediate type, their density is 840 kg/m^3, the sulphur content is 0.23 and 0.12%, the dissolved gas contents 29 m^3/m^3. The combustible part of the gas is 92%, the calorific value is 46.3 and 39.9 MJ/m^3, CH_4 73.1 and 78.6%, CO_2 1.4 and 0.9%, N_2 0.5 and 7.2%, the C_{5+} content 59 and 22 g/m^3.

Kelebia South (Kelebia-Dél). The *undersaturated oil reservoir* discovered by the Kel–7 well in 1970 was found in a stratigraphic trap in the fractured Permian meta-rhyolite basement and in the unconformably overlying Middle Miocene Sarmatian stage sandy limestone, conglomerate beds ("*Bácska horizon*") (OWC depth is 740 m bsl). The density of the naphthenic type oil is 950 kg/m^3, sulphur content 1.3%, dissolved gas content 20 m^3/m^3. The combustible part of the dissolved gas is 97.5%, the calorific value is 46.4 MJ/m^3, CH_4 73.1%, CO_2 1.4%, N_2 0.5%, C_{5+} 2 g/m^3.

Mórahalom. The free gas reservoir was discovered by the Móra–1 well in 1974, in basement rocks in a stratigraphic trap. The reservoir rock is Middle Triassic, dark grey calcareous dolomite and in the unconformably overlying Sarmatian stage limestone. The GWC depth is 1,206 m bsl. The combustible part of the gas is 80.0%, the calorific value is 35.1 MJ/m^3, CH_4 67.8%, CO_2 11.1%, N_2 8.9%, C_{5+} 39 g/m^3.

Ruzsa. The oil and gas field is built up of separated reservoir groups (Ruzsa–2, Ruzsa North, Ruzsa Middle, Ruzsa South). Reservoirs are situated in stratigraphic/lithologic traps formed in the Variscan and Mesozoic basement rocks and the unconformably overlying Neogene succession.

The first reservoir was discovered by the *Ruzsa–2* well in 1979, which was an *undersaturated oil accumulation* in a structural trap *in the Variscian metamorphic basement* and in the directly overlying *Miocene coarse clastics*. The OWC depth is 2,708 m bsl. The density of the oil is 839 kg/m^3, sulphur content 0.3%, dissolved gas content 50 m^3/m^3. The combustible part of the dissolved gas is 89.5%, the calorific value is 50.5 MJ/m^3, CH_4 50.4%, CO_2 9.4%, N_2 1.7%.

The *Ruzsa South–1* (Ruzsa-Dél–1) (2,845 m bsl OWC) and the *Ruzsa South–2* (Ruzsa-Dél–2) (2,715 m bsl) *undersaturated oil reservoirs* were explored by the Ruzsa–4 well in 1979. The reservoir rock of the lower accumulation is *Middle Miocene, silty sandstone*, that of the upper pool is *Lower Pannonian basalt agglomerate and tuff*. The type of accumulated oils are intermediate and paraffinic, their densities are 842 and 829 kg/m^3, the sulphur content is 0.10%, the dissolved gas content is 80 m^3/m^3. The combustible part of the gas is 86.6 and 98.5%, the calorific value is 45.0 and 51.0 MJ/m^3, CH_4 55.1 and 67.2%, CO_2 7.9 and 1.4%, N_2 5.5 and 0.1%, C_{5+} 150 and 99 g/m^3.

The *Ruzsa North–1* (Ruzsa-Észak–1) *free gas reservoir* was identified by the Ruzsa–5 well in 1978, and the *Ruzsa North–2* (Ruzsa-Észak-2) *oil reservoir* by the Ruzsa–8 well in 1980. The GWC depth of the free gas reservoir is at 2,170 m bsl, the reservoir rock is Middle Triassic dolomite and dolomite breccia and the overlying Middle Miocene conglomerate. The combustible part of the gas is 79.5%, the calorific value 31.2 MJ/m^3, CH_4 75.0%, CO_2 15.6%, N_2 5.0%, the C_{5+} content is 20 g/m^3. The OWC depth of the oil reservoir is at 2,068 m bsl. The reservoir rock is Lower Pannonian calcareous marl, marl. The density of the intermediate type oil is 864 kg/m^3. The combustible part of the gas is 92.3%, the calorific value is 50.0 MJ/m^3, CH_4 62.1%, CO_2 2.9%, N_2 4.8%, C_{5+} content 59 g/m^3.

Two *undersaturated oil reservoirs* have become known as *Ruzsa Middle* (Ruzsa-Közép). The *Közép–1 reservoir* was discovered by the Ruzsa–27 well in 1988, the OWC depth is 2,765 m bsl. The reservoir rock is Middle Triassic dolomite and dolomite breccia. The density of the intermediate type oil is 826 kg/m^3, the dissolved gas contents is 118 m^3/m^3. The combustible part of the dissolved gas is 82.4%, the calorific value is 42.5 MJ/m^3, CH_4 48.8%, CO_2 13.9%, N_2 3.8%, C_{5+} 184 g/m^3. The discovery well of the *Közép–2* oil reservoir was Ruzsa–15 (1984). The OWC depth is 2,637.5 m bsl. The reservoir rock is Middle Miocene conglomerate. The accumulated oil is intermediate type, its density is 849 kg/m^3, the dissolved gas contents 84 m^3/m^3. The combustible part of the dissolved gas is 92.3%, the calorific value is 52.5 MJ/m^3, CH_4 47.0%, CO_2 6.1%, N_2 1.5%, C_{5+} 803 g/m^3.

Szeged–Móraváros. The Szeged–1 discovery well was drilled in 1971. One oil reservoir has become known in a basement stratigraphic trap and one free gas reservoir in a pseudoanticline above the basement in lithologic trap. The OWC depth of the *Móraváros reservoir* is at 2,623–2,630 m bsl, the reservoir rock is Variscan metamorphite (gneiss, milonite, mica, quartzite) and the overlying Triassic dolomite, dolomite breccia, as well as Middle Miocene sandstone and conglomerate/breccia. The density of the paraffinic oil is 817 kg/m^3, the dissolved gas contents is 262 m^3/m^3. The combustible part of the dissolved gas is 90.2%, the calorific value is 45.3 MJ/m^3, CH_4 45.1%, CO_2 5.9%, N_2 3.9%, C_{5+} 1672 g/m^3. The GWC depth of the *free gas reservoir* is 2166 m bsl. The reservoir rock is Lower Pannonian sandstone. The combustible part of the natural gas is 96.0%, the calorific value is 39.7 MJ/m^3, CH_4 85.2%, CO_2 1.8%, N_2 2.2%, C_{5+} 80 g/m^3.

Üllés. The discovery well of the occurrence is the Üllés Ü–1 drilled in 1962. Three main reservoir horizons can be distinguished. The lower is the *Üllés-deep horizon*, where the reservoir rocks are Variscan metamorphites, Triassic and Lower Cretaceous carbonate rocks, Middle Miocene clastics and the transgressionally overlying Lower Pannonian calcareous marl, silty sandstone with basalt agglomerate and basalt tuff rocks. *Reservoirs in the Lower Pannonian sandstones* create one distinct horizon, and the uppermost level of the reservoirs can be found in the *Üllés Upper horizon* in Upper

Pannonian succession. The stored fluid is oil, rarely gas precipitate (distillate) and natural gas. Typical trap forms include the stratigraphic traps delineated by faults created in the elevated position Variscian and Mesozoic basin bottom and in the overlying Middle Miocene beds and the lithological traps found in the overlying more juvenile Miocene formations. A total of 16 oil deposits and 25 free gas deposits can be distinguished in the field as follows:

The *PR (pre-Neogene) reservoirs* include one oil and six free gas pools are known. The OWC depth of the oil reservoir PR–III/B is 2,475 m bsl, the reservoir rock is Variscan metamorphite. The density of the paraffinic-intermediate oil is 846 kg/m^3, the dissolved gas content is 160 m^3/m^3. The combustible part of the dissolved gas is 89.1%, the calorific value is 38.0 MJ/m^3, CH_4 73.6%, CO_2 11.8%, N_2 1.8%, C_{5+} 43 g/m^3. The GWC depth of the free gas reservoirs PR–I–VI is 2,639–3,192 m bsl. The reservoir rocks are Variscan metamorphites and the overlying Mesozoic carbonate rocks in a mixture, or only Triassic dolomite, dolomite breccia. The combustible part of the gases is 88.7%, the calorific value is 35.6 MJ/m^3, CH_4 81.7%, CO_2 8.8%, N_2 2.5%, C_{5+} 32 g/m^3. The amount of the gas condensate which can be extracted on the ground in normal state is 151 g/m^3.

The number of the *reservoirs* marked *M–II and M–III (Miocene)* is 19 in total, six are oil reservoirs (three with a minimum amount of cap gas) and 13 are free gas reservoirs. The OWC depth of the oil pools is between 2,062.5–2,250 m bsl. Reservoir rocks are Middle Miocene conglomerates and dolomite breccia. The density of the paraffinic–intermediate type oil is 817–849 kg/m^3, the dissolved gas contents 160–200 m^3/m^3. The combustible part of the dissolved gas is 89.7–97.9%, the calorific value is 38.7–68.5 MJ/m^3, CH_4 56.2–81.4%, CO_2 0–6.9%, N_2 0.7–3.0%, C_{5+} 47–644 g/m^3. The GWC depth of the free gas reservoirs is between 2,046– 2,925 m bsl. The reservoir rock is the same as the oil reservoirs. The combustible part of the gas is 88.5–91.4%, the calorific value is 34.6–44.2 MJ/m^3, CH_4 77.2–85.1%, CO_2 5.1–8.9%, N_2 0.5–4.0%, C_{5+} 15–223 g/m^3. The amount of the gas condensate is 125–193 g/m^3.

The *TR (transgression) reservoirs* include four undersaturated oil pools in Lower Pannonian calcareous marl (three accumulations) and silty sandstone. The OWC depth is between 1,973.5–2,285.0 m bsl. The density of the paraffinic or intermediate type oil is 779–843 kg/m^3, sulphur content 0.16–0.33%, dissolved gas content 47–180 m^3/m^3. The combustible part of the dissolved gas is 89.1–99.7%, the calorific value is 36.9–68.9 MJ/m^3, CH_4 62.7–81.4%, CO_2 0.1–8.6%, N_2 0.2–3.0%, C_{5+} 23–540 g/m^3.

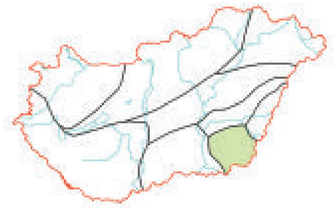
One undersaturated oil and three free gas *reservoirs marked Pl1 (Lower Pannonian)* are known. The OWC depth of the oil pool is 1,282.5 m bsl, the reservoir rock is Lower Pannonian sandstone. The oil type is paraffinic–intermediate, the density is 802 kg/m^3, dissolved gas content 160 m^3/m^3. The combustible part of the dissolved gas is 96.5%, the calorific value is 48.9 MJ/m^3, CH_4 contents 78.2%, CO_2 3.4%, N_2 0.6%, the C_{5+} content is 137 g/m^3. The GWC depth of free gas reservoirs is 1,693.0–1,821.5 m bsl. The reservoir rock is Lower Pannonian silty sandstone, sandstone. The combustible part of the gas is between 95.0–96.2%, the calorific value is 35.9–36.6 MJ/m^3, CH_4 93.5–93.9%, CO_2 1.8–2.7%, N_2 1.1–2.1%, C_{5+} 20–24 g/m^3.

Seven *reservoirs marked Ü–F* (Üllés-felső/Üllés Upper) are known, four oil and three free gas accumulations. Their accumulated hydrocarbon volume is subordinated compared to the reservoirs below them. Their respective OWC and GWC depths are between1,024–1,097 m bsl. The reservoir rock is Upper Pannonian shaly sandstone. The oil density is 741 kg/m^3, the dissolved gas content is 80 m^3/m^3. The combustible part of the dissolved gas is 95.5–98.1%, the calorific value is 38.6–55.1 MJ/m^3, CH_4 69.6–90.0%, CO_2 0.2–0.8%, N_2 1.0–2.9%, C_{5+} 0.2–2 g/m^3. The combustible part of the natural gas in the free gas reservoirs is 90.5–96.9%, the calorific value is 36.2–48.1 MJ/m^3, CH_4 70.3–85.8%, CO_2 0.5–2.4%, N_2 1.7–9.4%.

One small sized *oil reservoir* is known under the name *Üllés SW* (Üllés-DK) about a distance of 10 km from the Üllés field to the south-east, more in the neighbourhood of the Dorozsma field. The occurrence was discovered by the Ü-DK–2 well in 1975. The oil is accumulated in the Variscan metamorphic basement, its OWC depth is 3,144 m bsl. The density of oil is 805 kg/m^3, the combustible part of the dissolved gas is 75.7%, the calorific value is 33.1 MJ/m^3, CH_4 57.1%, CO_2 24.3%, N_2 4.4%.

Hydrocarbon exploration areas in Hungary — The Battonya–Pusztaföldvár High and the Békés Neogene Basin

Edit Babinszki, Zsolt Kovács



4.4

Exploration history

Lajos Lóczy Jr. was the first to deal with oil exploration in the south-western part of the Great Hungarian Plain in 1934. Eötvös torsion balance measurements were carried out from 1940–41. Gravity surveys after the World War II showed a positive anomaly between Battonya and Tótkomlós, which was interpreted as a basin basement high. The anticline of the basement high ridge slightly slopes from south-east to north-west; it is surrounded by the Békés Basin from the east and the Makó Trough from the west.

Drilling exploration was started with the deepening of the Tótkomlós–1 well in 1941. The well was abandoned due to technical problems, but natural gas and crude oil flowed to the surface and has proven the hydrocarbon potential of the area. After World War II, exploration continued in 1951, and in 1958 oil and gas production of commercial significance was started by the discovery of the Pusztaföldvár oil field (Kőrössy 1990a, 2005a, b). Since 1957 gravity and magnetic measurements and later geoelectric research between 1965–1970 were carried out by the Eötvös Loránd Geophysical Institute of Hungary (MÁELGI) in the area. The first seismic reflection measurement was performed by the Geophysical Company of the Hungarian–Soviet Oil Company (Maszolaj) along the AR–I regional measurement trace line in the Pusztaföldvár area.

T. Kovács (1965) provided a comprehensive overview of the subsurface geology of the Battonya region based on the data from the well drilled up to that date and characterised the four facies of the main oil and gas reservoir “Battonya-horizon” according to grain size and carbonate content. Kurucz (1977) assessed the formations building up the pre-Cenozoic basement of the basin between Pusztaföldvár and Battonya, and compiled the 1:100,000, and 1:200,000 scale maps of the Tiszántúl basement.

A detailed study was published by Teleki et al. (1994) on the geological and hydrocarbon geological properties and hydrocarbon potential of the region. Mol Hungarian Oil and Gas Plc carried out various projects in some parts of the area in the 1990s and the 2000s. The aim of the explorations in the Battonya–Pusztaföldvár North exploration area (Szentgyörgyiné ed. 1997) was to enhance the level of information in the area. Surface geophysical (gravity, magnetic, geoelectrical, seismic) measurements were performed in the course of the research. Eight new wells were also drilled (Oros–1–3; Oros-DNy–1; Pf–1; Nsz–1–3), but all of them proved dry.

During the exploration of the Tótkomlós South area (Tatárné et al. 1997) two new wells were drilled: the T-D–1 (oil producing) and the T-D–2 (dry). In the Battonya–Pusztaföldvár SW exploration area (Tatárné et al. 1999a) geoelectrical, 2D and 3D seismic acquisitions were carried out and seismic profiles were revaluated, 16 new wells were drilled, 6 of which produced oil, 4 natural gas and 6 proved dry. In the Battonya–Pusztaföldvár East area (Tatárné et al. 1999b) 2D and 3D seismic and radon measurements were implemented. One new well had drilled (Med–4), which produced oil.

In the Gádoros area gravity, geoelectrical, magnetic and seismic research was carried out and seismic profiles were re-evaluated. No new wells were drilled. No hydrocarbon reservoirs were discovered in the area, only traces of combustible gas were revealed, referring to a highly mature source rock. Conditions of hydrocarbon generation in the surrounding basins are present. The area has a high geothermal potential, as well (Kiss 2002).

The purpose of the research in the Battonya–Pusztaföldvár area in the 2000s (Szentgyörgyiné ed. 2010) was to enhance the level of information from the region. In the course of the investigations 2D seismic profiles were revaluated and 3D seismic measurements were carried out. 12 exploration wells were deepened, 9 of which proved productive.

Up to now, 183 hydrocarbon reservoirs of various areal extent have been explored in 30 fields by more than 700 drillings. At present explorations are being carried out in the northern part of the Battonya–Pusztaföldvár Ridge by the Mol Plc, and by Vermilion Energy Inc in the southern part holding the respective concessions.

Geological overview

The buried Battonya–Pusztaföldvár basement ridge is built up of nappe structures, in which the material of the metamorphic basement complex overthrusted to the Palaeo-Mesozoic sequence by northern, north-western vergence. The area belongs to the Tisza Mega-unit with the greatest part associated with the nappe-imbricated structure Békés–Codru Unit. Only the north-western corner of the area stretches over to the Villány–Bihor Unit. The formation of the nappe system

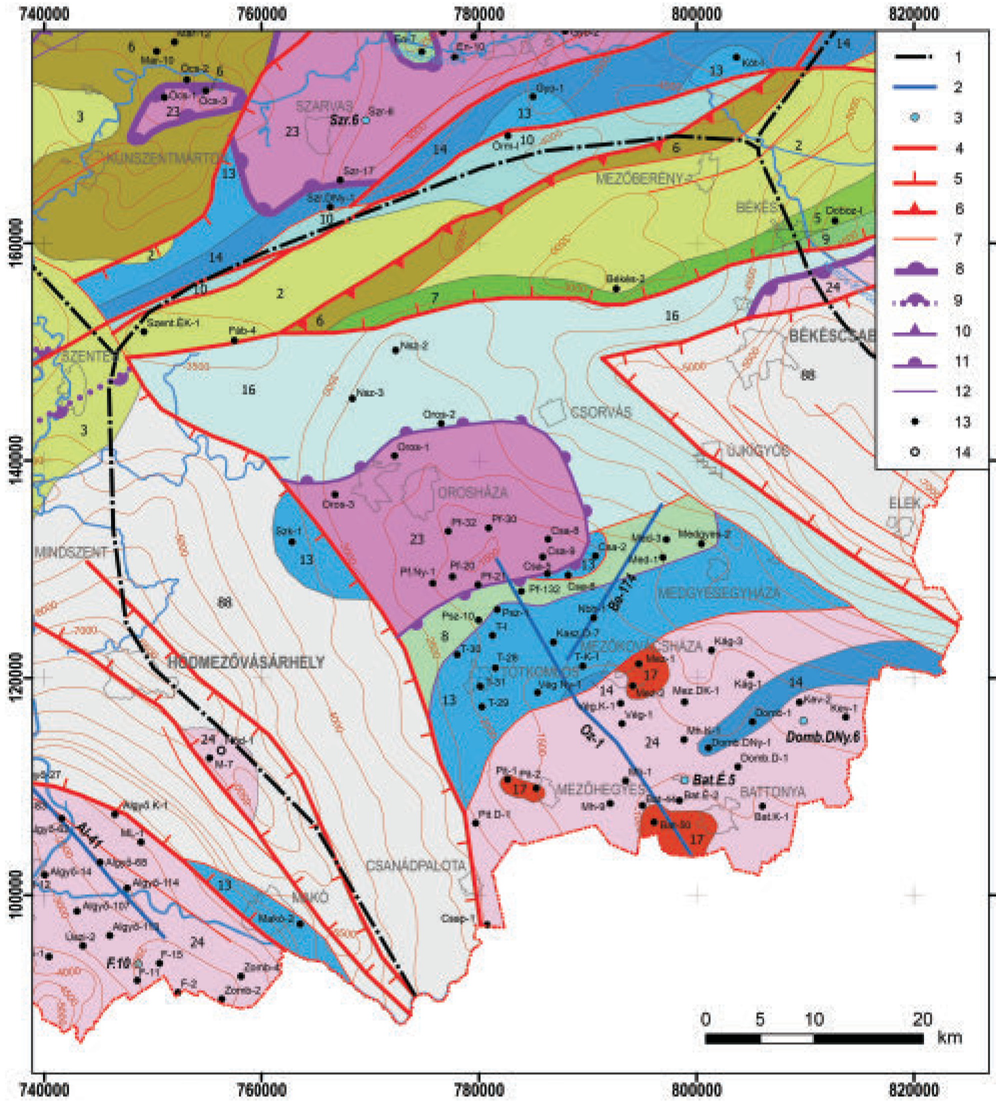


Figure 4.4.1. Pre-Cenozoic geological map of the Battonya–Pusztaföldvár area (HAAS et al. 2010)

Elements of legend: 1. boundary line of the Battonya–Pusztaföldvár area, 2. trace line of the sample 2D seismic profiles in this chapter, 3. location of wells including sample geophysical logs on the figures in this chapter,, 4. second-order Cenozoic tectonic line, 5. second-order Cenozoic normal fault, 6. second-order Cenozoic overthrust, 7. third-order Cenozoic tectonic line, 8. first-order Mesozoic nappe boundary, 9. first-order Mesozoic nappe boundary, covered, 10. second-order Mesozoic overthrust, 11. second-order Mesozoic nappe, 12. third-order Mesozoic tectonic line, 13. wells hit the basement, 14. wells stopped above the pre-Cenozoic basement

Legend for geological formations: 2. Senonian flysch, 3. Senonian continental, shallow- and deep-marine (bathyal) formations, 5. Lower Cretaceous limestone of platform facies, 6. Lower Cretaceous basic volcanics and their redeposited marine sediments, 7. Lower Cretaceous pelagic marls, limestones, 8. Jurassic–Lower Cretaceous pelagic limestones, marls, 9. Middle Jurassic – Lower Cretaceous pelagic limestones, cherty limestones, 10. Lower–Middle Jurassic pelagic, fine siliciclastic formations, 13. Middle Triassic shallow-marine siliciclastic and carbonate formations, 14. Lower Triassic siliciclastic formations of fluvial and delta facies, 15. low-grade metamorphic Mesozoic formations, 16. Mesozoic formations without subdivision, 17. Permian rhyolite, 23. Variscan metamorphite formations (gneiss, mica, amphibolite), 24. Variscan crystalline rocks without subdivision, 88. inadequately evaluable or unknown basement

is predominantly the result of the Cretaceous (Austrian) compressional tectonics. Within the nappe structure, tectonic structures of NE–SW direction occur; Cenozoic transverse faults of NW–SE strike can also be observed (Figure 4.4.1).

The rock masses of the basement core complex faulted down from the core gravitationally in the syn-rift phase of the development of the Pannonian Basin — during the large-scale extension, generally evaluated as Middle Miocene (HORVÁTH, RUMPLER 1984, NEMCOK et al. 2006, TARI et al. 1999). This detached rock mass fragment constitutes the Battonya–Pusztaföldvár High, to the NE and SW of which the two deepest Neogene basement depressions of Hungary are situated: the Békés Basin and the Makó Trough (Figure 4.4.1). The basins are of halfgraben structure, thus the tectonic lines bounded the basins on one side consist of a main fault with low number of planes and several small faults on the other side (POSGAY et al. 1996, HAJNAL et al. 1996). This arrangement influences the structure of the ridges between the depressions as well, thus the south-western side of the Battonya–Pusztaföldvár High slid down most probably with a series of lesser normal faults toward the Makó Trough (Figure 4.3.2).

Basement formations

The basement of the area south of the Pitvaros–Mezőkovácsháza–Kunágota line up to the national border is made up of the rocks belonging to the Battonya Complex: wells drilled migmatic–granitic rock bodies of large areal extent. Formation of the granite intrusion can be associated with the Early Palaeozoic, Variscan movements. The age of the complex is 386 Ma ±10% (STEGENA, KISS 1967). The granite complex is surrounded by a migmatite zone on the NE, N and SW side (SZEDERKÉNYI 1997, SZENTGYÖRGYINÉ ed. 2010). The Lower Triassic sequence of the complex occurs as a narrow strip which was pinched out between the nappes having north vergence. The theoretic stratigraphic columns of the area are shown in Figure 4.4.2.

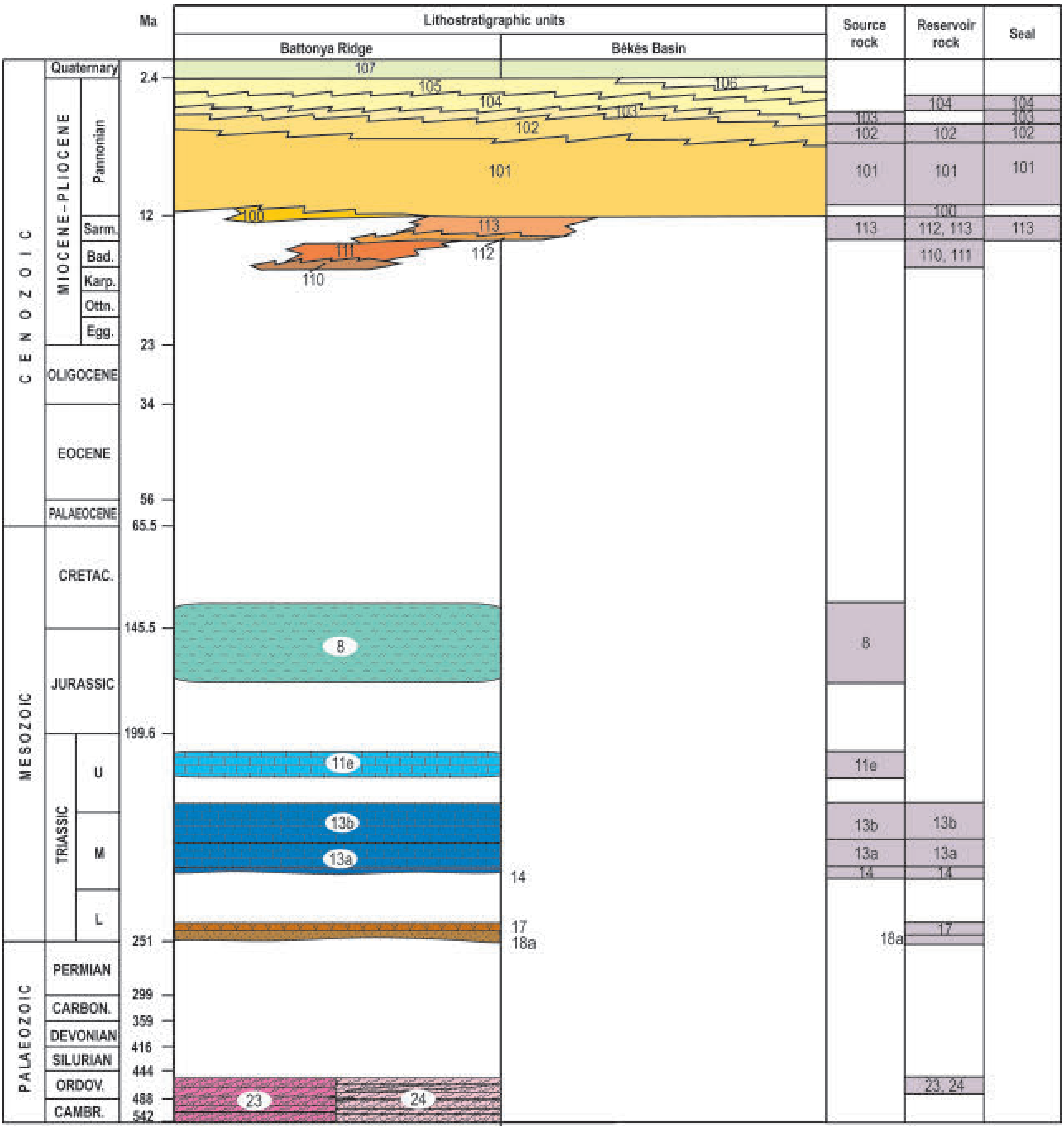


Figure 4.4.2. Lithostratigraphic column of the Battonya–Pusztaföldvár High and the Békés Neogene Basin and the elements of the hydrocarbon systems

Legend: V V V – traces of volcanic activity. Formations seen in the profile: 8. Jurassic – Lower Cretaceous pelagic limestones, marls; 11. Jurassic shallow-marine and condensed pelagic limestone formations; 13. Middle Triassic shallow-marine, siliciclastic and carbonate formations; 14. Lower Triassic siliciclastic formations of fluvial and delta facies; 17. Permian rhyolite; 18. Permian continental clastic formations; 23. Variscan metamorphites (gneiss, mica, amphibolite); 24. Variscan crystalline rocks without subdivision; 110. Lower Badenian basal breccia of abrasion facies; 111. Middle Badenian shallow-marine biogenic limestones; 112. Sarmatian transgressive basal debris; 113. Sarmatian shallow-marine carbonate and siliciclastic beds; 100. Pannonian littoral conglomerates, sandstones; 101. Pannonian open lake calcareous marls, marls, argillaceous marls; 102. Pannonian deep-water succession of turbidite origin; 103. Pannonian sediments of delta-slope facies; 104. Pannonian siliciclastic succession of littoral facies; 105. Pannonian siliciclastic succession of fluvial and lacustrine facies; 106. Pannonian siliciclastic beds of fluvial facies; 107. Quaternary sediments

In the Tótkomlós–Kaszaper–Nagybánhegyes–Medgyesbodzás–Medgyesegyháza line in a 10–15 km wide range, the surface of the basement is made up of Mecsek-type Lower and Middle Triassic, as well as Jurassic rocks (sandstone, limestone and dolomite), moreover, Lower Cretaceous pelagic limestone and marl formations. In the Csanádapáca–Kardoskút–Orosháza area the basement is built up of the metamorphic core complex (tectonically strongly compressed, folded, milonitic gneiss and mica), and further to the north–north-east it is made up of Mesozoic formations again. To the north of the Szentes–Békés line the basement is formed by the Mesozoic formations of the Villány–Bihor Unit.

In the area the Permian is represented mainly by the Gyűrűfű Rhyolite Formation, which penetrates the granite in many places. Its formation can be associated with the beginning of the Alpine orogeny and the continental rifting preceding the opening up of the Neotethys Ocean: volcanics were flown onto the surface through basement faults. The fractured top zone of the rhyolite is weathered; it can be found in the area underlying in general the Pannonian basal formations.

Siliciclastic beds of the Lower Triassic Jakabhegy Sandstone Formation — made up of fluvial and deltaic sediments — unconformably overlie the granitic basement complex in some places. Due to the further subsidence of the basin, the Anisian stage of the Middle Triassic is already represented by the Szeged Dolomite Formation of shallow-marine lagoon facies, whereas the Ladinian and Carnian stages by the Csanádapáca Dolomite Formation which was also deposited in lagoon environment. Variegated clay-shale and anhydrite underlie the Triassic dolomites in several well successions, which can be identified as the Hetvehely Dolomite Formation deposited in the shallow-marine, tidal zone and sabkha environment.

The Jurassic facies is locally represented by the crinoideal Menyháza Limestone Formation and thick Lower Jurassic calcareous marl succession overlying the Triassic dolomite sequence. The Upper Jurassic – Lower Cretaceous Calpionella-, and Radiolaria-bearing Pusztaszőlős Marl Formation, and the Pusztaföldvár Marl Formation are also known in the area.

In the northern part of the area Mesozoic formations of the Villány–Bihor Unit can be found in the basement: beside the clastic Lower Triassic rocks (Jakabhegy Sandstone Formation), the shallow-marine Middle Triassic succession, characterised by siliciclastic and carbonate rocks (Csanádapáca Dolomite Formation), and the Lower–Middle Jurassic pelagic formations and Lower Cretaceous pelagic marl and platform limestone also occur also in a strip.

Basin fill sediments

The worm-eye map of the Cenozoic formations of the area (TANÁCS, RÁLISCH 1990) nowhere indicates any formations older than the Badenian or uncertainly classified formations older than the Karpatian–Badenian. Accordingly, a sedimentary gap — covering the entire Palaeogene — can be assumed, the reason of which is that the area became elevated and turned to a dry land after the nappe movements in the course of the Late Cretaceous Austrian orogene phase.

The Miocene formations overlie the erosion surface of the pre-Cenozoic basement with significant sedimentary gaps. Their facies, areal extension and thickness is determined by the tectonic processes affecting the basement during the Miocene, and its morphology. Their continental denudation must also be taken into account due to the end-Middle Miocene movements.

As a consequence of the structural movements starting most probably at the Karpatian–Badenian boundary, thin ridges of E–W strike, enclosing an acute angle with the main structural directions, and the accompanying trough were formed within the structural zone built up of the Mesozoic formations. In connection with tectonic zones, the surface of the basement — made up of metamorphic complexes —, became uneven. Pre-Badenian unconformity and sedimentation repeatedly starting in the Badenian indicate tectonic movements in the Early Badenian. The basal formation of the Badenian sequence consists of coarse conglomerate, deposited in the troughs between the basement blocks moving away from each other. Its stratigraphic position is varied, it contains mainly the debris of the basement rocks, usually with red clay as binding material.

The Badenian marine sedimentation took place in an archipelago environment, represented by a variety of facies. The Abony Formation made up of conglomerate, calcareous sandstone and silt represents the base of the transgressive sequence. A few wells explored biogenic limestone of the Ebes Formation, as well. An important feature of the Badenian formations in terms of structural geology is the extremely diverse thickness and depth.

The Sarmatian coarse clastic rocks among the sediments formed in the course of the syn-rift subsidence on the Battonya–Pusztaföldvár High ridge are known only from six wells, and considering their depth interval (1,513–2,735 m) they are quite dispersed. The wells reaching the Sarmatian penetrated conglomerate–sandstone beds (Dombegyháza Formation), and a sandy limestone, calcareous sandstone succession with tuff intercalations (Hajdúszoboszló Formation). Despite the scattered occurrence and small thickness of the Sarmatian formations which can be distinguished only with uncertainty, these formations demonstrate that sedimentation took place also during the Sarmatian in the Battonya–Pusztaföldvár High area (MAGYAR et al. 2004).

The schematic stratigraphic–sedimentological profile of the Pannonian formations in the southern part of the Great Hungarian Plain is shown by Figure 4.3.3. The older basin sediments expanded high onto the structure on the slope of the ridge. At the beginning of the Pannonian sedimentation the Battonya–Pusztaföldvár High was a land. The Pannonian sediments overlie either directly the Palaeozoic–Mesozoic basement complex, as seen on the Oz–1 seismic profile running along the Battonya–Pusztaföldvár Ridge (Figure 4.4.3), or transgraded onto the sporadically appearing Miocene formations, as seen in Be–174 profile, the basement of which descends from the ridge towards the Békés Basin (Figure 4.4.4).

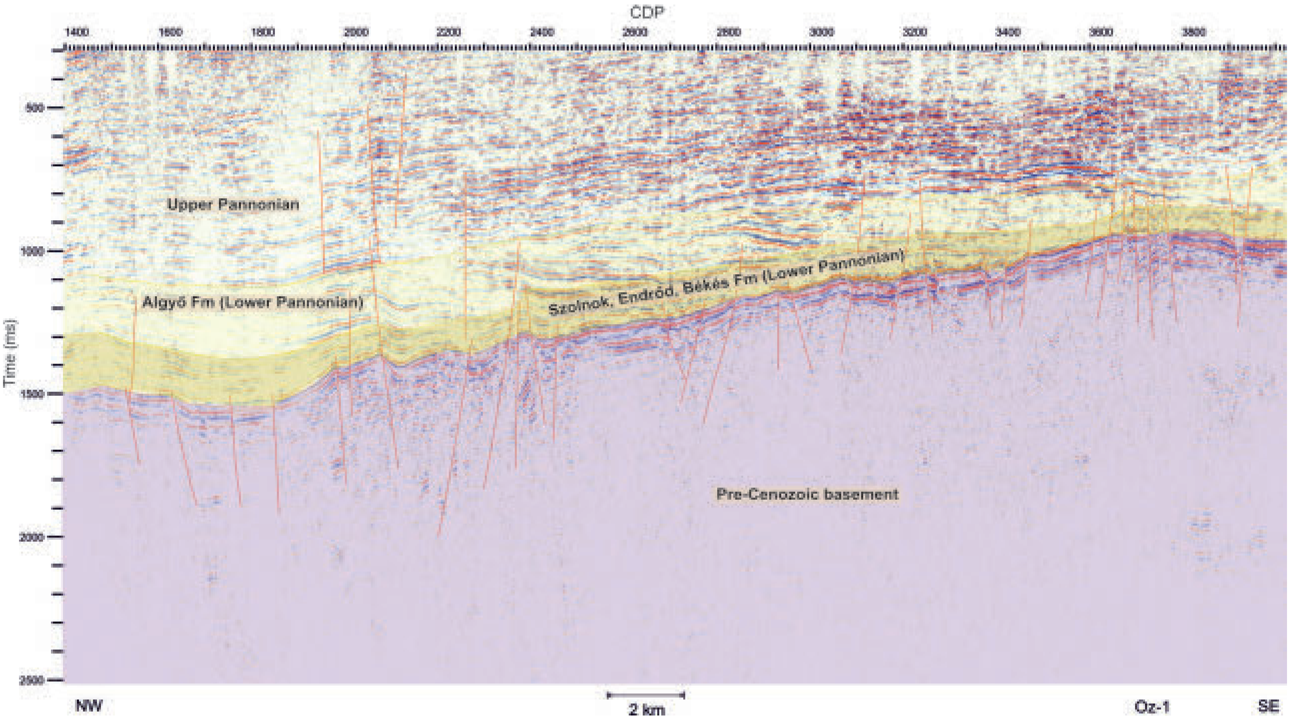


Figure 4.4.3. The Oz-1 seismic time section of NW-SE direction running along the Battonya-Pusztaföldvár High (The trace line of the profile can be seen on Figure 4.4.1)

The abrasion conglomerate and sandstone beds (Békés Conglomerate Formation) at the base of the Pannonian sequence is found in the area in patches only. In contrast to this, the Endrőd Marl Formation can be found in almost all of the wells.

A thin basalt agglomerate overlies the calcareous marl beds in the Magyarbánhegyes (Mbh)–1 well (Kecel Basalt Formation), a sign of the Pannonian volcanism on the Battonya–Pusztaföldvár High.

The deep-water marls are overlain by the turbidite succession of the Szolnok Sandstone Fm consisting of the alternating layers of fine-grained sandstone and argillaceous marl. The formation developed in reduced thickness on the elevated ridge

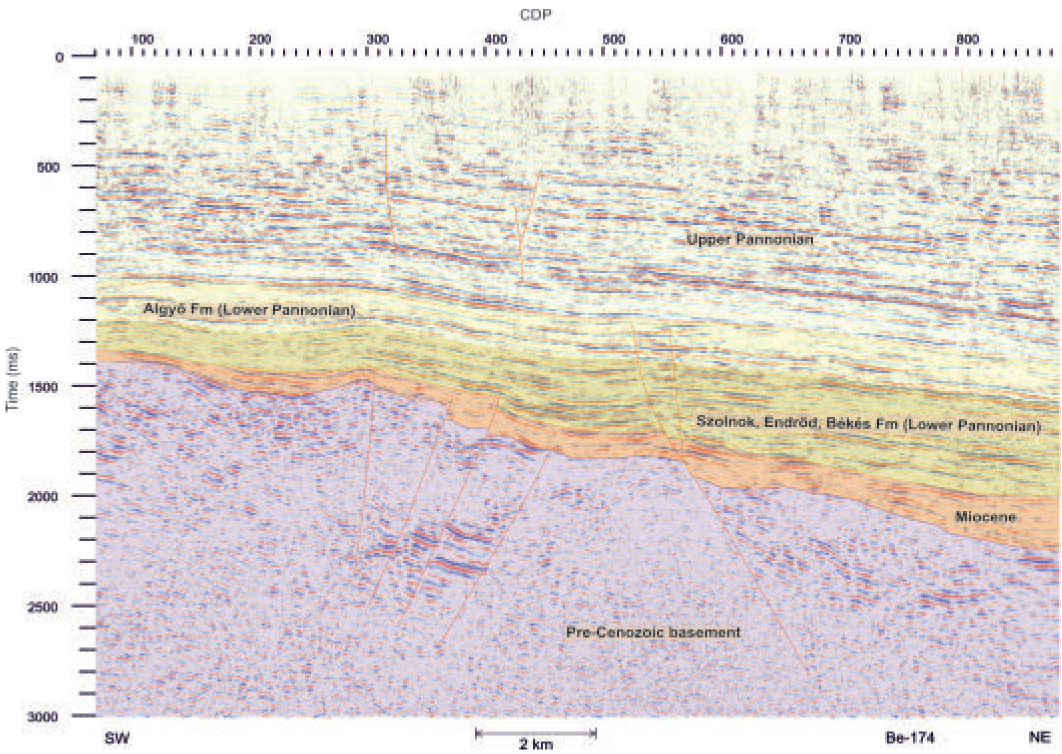


Figure 4.4.4. The Be-174 seismic time section of SW-NE direction running from the Battonya-Pusztaföldvár High towards the Békés Basin (The trace line of the profile can be seen on Figure 4.4.1)

(approx 100 m), but may be present in the surrounding troughs in a thickness of up to more than 1,000 m just as well. The turbidites are covered by the Algyő Formation deposited on the basin slope with an angle of approx 5–20° and on the delta slope.

In total, the so-called Lower Pannonian succession (Békés Conglomerate, Endrőd Marl, Szolnok Sandstone, Algyő Formation) is approximately 600–800 metres thick in the area of the Battonya–Pusztaföldvár High (Figure 4.4.3–4.4.4), whereas towards the Makó Trough it can reach a thickness of 1,500–2,000 metres, and 3,000 metres towards the Békés Basin.

Along the margins of the sedimentary basin, sedimentation took place in a nearshore environment. As a result of this predominantly deltaic sediments were deposited. The Upper Pannonian succession (Újfalu, Zagyva, Nagyalföld Formations) is about 600–800 m thick in the area of the Battonya–Pusztaföldvár High, but may reach as much as 2,000 metres towards the basins.

In the Quaternary the fluvial, lacustrine and paludal sedimentation continued in the area. As a result of the SW–NE compression elevation and erosion occurred on the basement ridges, while the troughs underwent further, intensive subsidence. Sedimentation was uninterrupted in the deep basins, the thickness of the Quaternary sediments may reach 600–800 metres, while on the elevated ridge the sequence is much thinner due to the denudation (just reaching 150 metres). The Maros river built an alluvial cone in the area during the Late Pleistocene. Loess and loessy sand was accumulated in the Würmian (URBANCSEK 1977). Re-deposition of the loess takes place in the Holocene beside fluvial sedimentation.

An overview of hydrocarbon geology

The hydrocarbon accumulation zone in the area is associated with the relatively flat, 10–15 km wide and approximately 100 km long, tectonically divided palaeo-geomorphological ridge of the pre-Neogene basin basement with NW–SE strike,

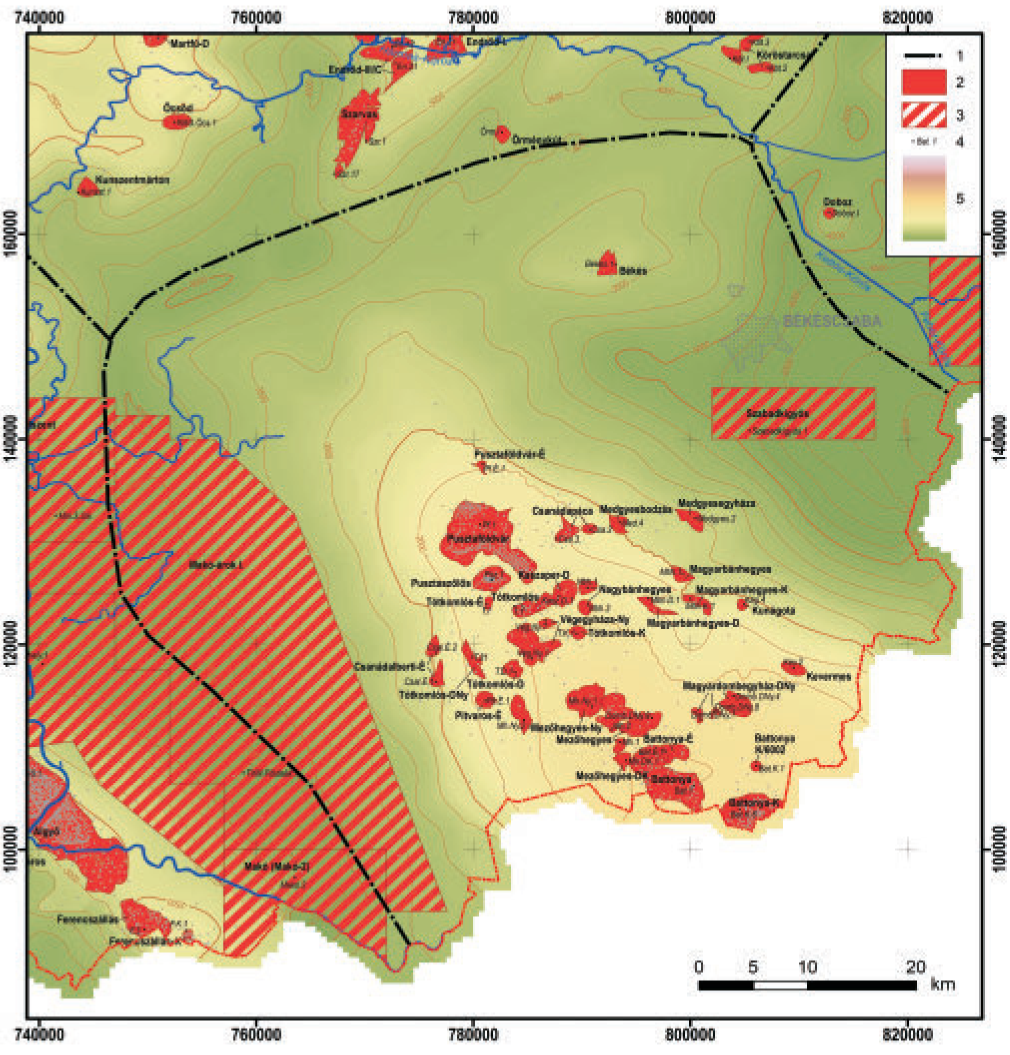


Figure 4.4.5. Location of hydrocarbon fields and the depth of the pre-Cenozoic basement on the Battonya-Pusztaföldvár High and surroundings

Legend: 1. Boundary of the sub-basin area; 2. Conventional hydrocarbon field, 3. Unconventional hydrocarbon mining plots; 4. Discovery well; 5. Depth of the pre-Cenozoic basement

elevating in south-eastern direction and the limbs thereof. Occurrences with the largest area and resources are in the axial line of the ridge (Figure 4.4.5).

Source rocks

The hydrocarbons accumulated in the reservoirs of the area might be generated largely from deep basins surrounding the basement high range, mainly from the east, from the Békés Basin, and from the west, from the Makó Trough. The main source rocks are the Middle Miocene and the Lower Pannonian calcareous marl, marl, argillaceous marl and siltstone strata of the several thousand metres thick sediments of the basins (DANK 1988). The fact that the bottom parts of the deep basins were hardly explored by wells causes uncertainty, therefore the geochemical analysis data from the main source area are incomplete. The organic matter contents and maturity data of the source rocks are described in several publications (HORVÁTH et al. 1988, CLAYTON et al. 1994a, b; Figure 4.4.6).

The Mesozoic, Triassic–Jurassic carbonate rocks in the basement of the area containing a low amount of organic matter can be characterised by different levels of thermal maturity, they are in general overmatured. The CO_2 gas which provides a substantial part, up to 70% of the CO_2 content of the natural gas in the hydrocarbon reservoirs accumulated in the proximity of the basement complex surface on the ridge range might originate from the deep structural position carbonate beds (KERTAI, 1972).

Badenian and Sarmatian calcareous clay sediments have varying potential, they already released a substantial ratio of their potential. Argillaceous marl beds (Makó Formation) placed into the Badenian stage earlier and into the base Lower Pannonian subsequently (BADICS et al. 2011a, b) can also be considered as oil and natural gas generating source rocks.

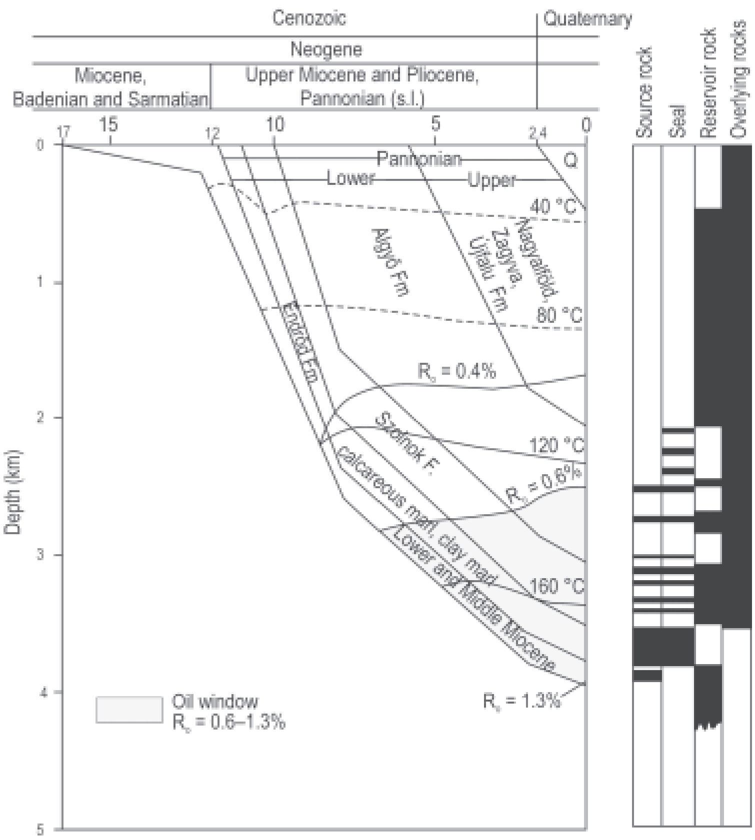


Figure 4.4.6. The burial history model of the Békés Basin and the elements of the hydrocarbon systems (adapted from HORVÁTH et al. 1988, CLAYTON et al. 1994a)

Lower Pannonian shallow and deep-water calcareous marl and argillaceous marl (Endrőd Marl Formation) is the key oil and gas source rock in the area as it could mostly preserve the hydrogen contents of its organic matter due to the quick subsidence of the basin basement (BADICS et al. 2011a, b).

The value of the total organic carbon content (TOC) varies in general in the 0.5–2% range. The fine grained calcareous marl (Tótkomlós Calcareous Marl Member) constituting the base formation, has a TOC value of 2–4%. The argillaceous marls of the delta foreground (Endrőd Formation Nagykörű Clay Marl Member) are currently in the oil window, in the deep basin in the wet gas zone (Figure 4.4.6). Thick argillaceous marl beds in the deep zones of the Makó Trough and Békés Basin can be considered as a large mass of matured source rocks (Figure 4.4.4).

The Lower Pannonian fine grained sediments (Szolnok Formation, Algyő Formation) deposited in the overburden of the Endrőd Marl has variable organic matter contents, mainly below 1%, which can be considered as a source rock with scruple only.

The fine grained sediments of the Upper Pannonian sedimentary sequence hold varying TOC values occasionally ranging up to even 10%, but their maturity is insufficient due to the shallow burial and low temperature, they are not suitable for thermal hydrocarbon generation. Substantial amount of natural gas of biogenic origin could be accumulated in delta plain facies sandstones.

The organic matter of source rocks is predominantly of the Type III kerogen containing, gas generating, and mixed gas/oil generating type. The pre-Pannonian (Middle Miocene) source rocks and the Endrőd Marl Formation deposited on the base of the Pannonian stage contain Type II kerogen only partially (SZENTGYÖRGYINÉ et al. 2010).

Migration

Most of the natural gas and oil fields of the Battonya–Pusztaföldvár High are found in rocks with immature organic material, in relatively shallow depth of 1.5–2.5 km, above the basin basement high, or occasionally on the flanks of the elevations. These hydrocarbons derived from the matured organic matter of the deep troughs nearby (hydrocarbon kitchens), and migrated upwards a few hundred metres. Based on model calculations a substantial amount of hydrocarbon migrated from the source rock downwards and/or laterally, then they might have been trapped in the basin basement rocks, and at the edges of the deep troughs in relatively shallow depth (2–4 km).

The primary migration surfaces between the deeper lying source rocks and the higher position reservoirs are the unconformity surfaces formed on the top Palaeozoic–Mesozoic basement complex, and on the base of the Pannonian formations. Lateral migration of hydrocarbons is made possible by the fractured, weathered and eroded surface of the pre-Cenozoic basement of any time, and the higher permeability zone of the overlying abrasion surfaces with the effect of hydrodynamic water flow among these surfaces. The vertical migration is assisted by the faults between the basin basement and the reservoir rocks (SPENCER et al. 1994, SZENTGYÖRGYINÉ et al. 2010).

The porous, clastic and carbonate reservoir beds close to the top zone of the Middle Miocene (pre-Pannonian) strata can be filled up with hydrocarbons migrating on the pre-Pannonian Miocene – Lower Pannonian boundary layer from the deeper position Miocene and Lower Pannonian source rocks.

The more silty, fractured sections in the base Lower Pannonian calcareous marl (Tótkomlós Calcareous Marl Member) might have been saturated by the migration of hydrocarbons generated in a small distance in that beds. Hydrocarbons, generated in Lower Pannonian clay-marl in the deeper parts of the basin, accumulated after brief secondary horizontal migration in the delta foreground turbidite sandstone successions (Szolnok Formation). Mostly biogenic or lower matured thermal gases were accumulated in the Upper Pannonian delta plain facies sandstones (Újfalu Formation) generated in pelites intercalated with the sandstones.

Reservoir rocks

The most important reservoir rocks in the area are as follows (TATÁRNÉ et al. 1999a, b, SZENTGYÖRGYINÉ et al. 2010, Figure 4.4.4, 4.3.10):

— The upper, fractured zone and fragmented, weathered surface of the Palaeozoic basement rocks, Palaeozoic metamorphic granites (Battonya Complex), Permian rhyolite, rhyolite tuff (Gyűrűfű Rhyolite Formation);

— Lower Triassic fractured sandstones (Jakabhegy Sandstone Formation), Middle Triassic fractured, brecciated dolomites (Szeged and Csanádapáca Dolomite Formation);

— Middle–Upper Miocene, Badenian and Sarmatian conglomerates, sandstones, biogenic limestones (Abony, Ebes Formation);

— Lower Pannonian basal conglomerates and sandstones (Békés Formation);

— Lower Pannonian fractured basal calcareous marls, argillaceous marls (Endrőd Formation, Tótkomlós Calcareous Marl Member);

— Lower Pannonian delta foreground facies, turbiditic sandstones (Szolnok Formation);

— Upper Pannonian delta plain facies, various types of point bar and river bed sandstone successions, poorly consolidated sands (Újfalu Formation).

The most significant hydrocarbon reservoir horizon of the Battonya–Pusztaföldvár High is the fractured top zone of the Palaeo–Mesozoic basin basement and the directly overlying Pannonian basal conglomerate–sandstone–calcareous marl sequence, or, in a lesser extent the pre-Pannonian Miocene and the Lower Pannonian base coarse clastic sedimentary sequence (60% of the known hydrocarbon resources, 96.5% of the oil resources are accumulated in this horizon). With the exception of the Földvár-alsó reservoirs oil accumulations can only be found in the Békés Conglomerate Formation and the Endrőd Formation Tótkomlós Calcareous Marl Member, as well as in the pre-Neogene underlying basement rocks which are hydrodynamically interdependent with the above mentioned formations. Oils are predominantly of paraffinic type, their density varies in a range of 808–875 kg/m^3. The Tótkomlós Calcareous Marl Formation is a regionally typical reservoir rock, traps were formed in it due to the changing permeability of the calcareous marl. Less significant reservoirs can be found in the Middle Miocene clastics and carbonates and in the Middle Triassic basement rocks (PAP et al. 1998).

Dissolved gases of oils and the free gas accumulations belong to the combustible mixed gas category, typically due to the high and substantially variable CO_2 content. Reservoir rocks and fluid contents of accumulations occur in varied combinations. Substantial combustible free gas reservoirs are found in the younger formations of the Pannonian stage: in open water pro-delta sandstones (Szolnok Formation) and delta plains sandstones (Újfalu Formation) (JUHÁSZ et al. 1997, SZENTGYÖRGYINÉ ed. 2010).

Porosity values of the different reservoir rocks are the following: the porosity of the basement metamorphic rocks are around 5%, but in some fractured and brecciated parts rarely reach 15–22% just as well; of the upper, karstified, weathered

part of the Mesozoic carbonate basement rocks, mainly dolomites is approximately 9%; of the pre-Pannonian Miocene reservoirs are 5%; of the base conglomerates, base sandstones within the Lower Pannonian beds is in general 7–10%, sometimes reaching 20%, that of the fractured calcareous marls varies at around approximately 5–7%, of the sandstones mostly around 13 and 22%. Upper Pannonian sandstones have 13–33% porosity.

Seal rocks

Seals of the reservoir formations are clays, silts and argillaceous marls building up the bedrock and cap rock of the reservoir rocks and are impermeable under the hydrostatic pressure conditions. The closure is provided by clay-marls interrupting the sandstones in the case of the domed Lower Pannonian traps and the reservoir becoming impermeable and argillisation or thinning out in the case of the lithological traps. Although they appear sporadically, but in certain areas Mesozoic argillaceous marls, calcareous siltstones, mudstones and the Miocene clay-bearing–silty horizons are also important.

Trapping

Hydrocarbons migrated into the structures of the fractured blocks of the basin basement, and into the stratigraphic traps in sandstones of the anticlines developed as a result of folding and compaction (Dank 1988, Horváth, Tari 1999). Hydrocarbons migrated from deeper zones had arrived to their final trapping locations in accordance with the actual morphological conditions of the carrier horizons, and accumulated mainly in combined structural/stratigraphic traps in the area of the Great Hungarian Plain (Clayton et al. 1994b). The most common trap structure is the buried dome combined with occasional lithological capping (Juhász et al. 1997).

Hydrocarbon occurrences of the Battonya–Pusztaföldvár High and the Békés Neogene Basin

The Battonya–Pusztaföldvár High

Data characterising the discovered reservoirs (hydrocarbon composition, calorific value, etc.) basically are originated from the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ), in other cases the source is indicated.

Battonya. The field situated in the neighbourhood of the national border was discovered by the Bat–1 well in 1959. Seven reservoirs are known in this field. The lowest is the oil reservoir with gas cap developed in the *Battonya horizon* on the granitic–metarhyolitic Variscan basement and in the overlying basal conglomerate–sandstone (Békés Conglomerate Formation) and calcareous marl (Endrőd Marl Formation Tótkomlós Calcareous Marl Member) succession. The boundary between the accumulated oil and the underlying water body (OWC) is situated in a depth of 927 metres below sea level (m bsl). The oil is of paraffinic type, its density is 829 kg/m^3. The dissolved gas content is 145 m^3/m^3, the sulphur content 0.28%. The combustible part of the dissolves and cap gas is 52.2%, the calorific value is 20.9 MJ/m^3. The methane (CH_4) content of the gas is 46.7%, the carbon dioxide (CO_2) content is 44.3%, and the nitrogen content (N_2) is 3.5%.

Six additional free gas reservoirs (Battonya-felső (upper) –1–6 reservoirs) can be found in the Upper Pannonian clay-bearing sandstone formation reservoirs, in a depth range characterised with the 403 and 645 m bsl gas water contact (GWC). The CH_4 content of the accumulated gas is 97.6%, CO_2 content is 0.1–2%, N_2 content 0.1–2%, the calorific value is 34.5–35.3 MJ/m^3.

Battonya North (Battonya-Észak in Hungarian**).** The Bat-É–1 well discovered one free gas reservoir in 1982 in Lower Pannonian silty sandstone. The GWC depth is 649 m bsl. The CH_4 content of the gas is 97.3%, CO_2 0.3%, N_2 2.3%, the calorific value is 33.5 MJ/m^3.

Figure 4.4.7 presents geophysical well logs typical for the area.

Battonya East (Battonya-Kelet). An oil reservoir with gas cap and two free gas reservoirs are known in the *Battonya horizon*. The oil accumulation is in calcareous marl (Endrőd Formation Tótkomlós Calcareous Marl Member). In Lower Pannonian layers are the free gas reservoirs, the exploration wells are the Bat-K–1 (1961) and the Bat-K–6 (1970). The OWC depth of the Battonya horizon oil reservoir is 888 m bsl. The density of the paraffinic type oil it 800 kg/m^3, the sulphur content 0.18%, dissolved gas content 85 m^3/m^3, the calorific value is 22.6 MJ/m^3. The CH_4 content of the gas is 47.4%, CO_2 42.9%, N_2 3.7%. The C_{5+} contents (straight chain hydrocarbon compound containing 6, or more carbon atoms) is 90 g/m^3. The two free gas reservoirs are of similar quality with high CO_2 content. Their GWC depth is 796.5 and 798 m bsl, respectively. The reservoir rock is clay-bearing sandstone. The combustible part of the gases is 44%, CO_2 content 53.9 and 56.0%, respectively. The gas contains hydrogen sulphide as well.

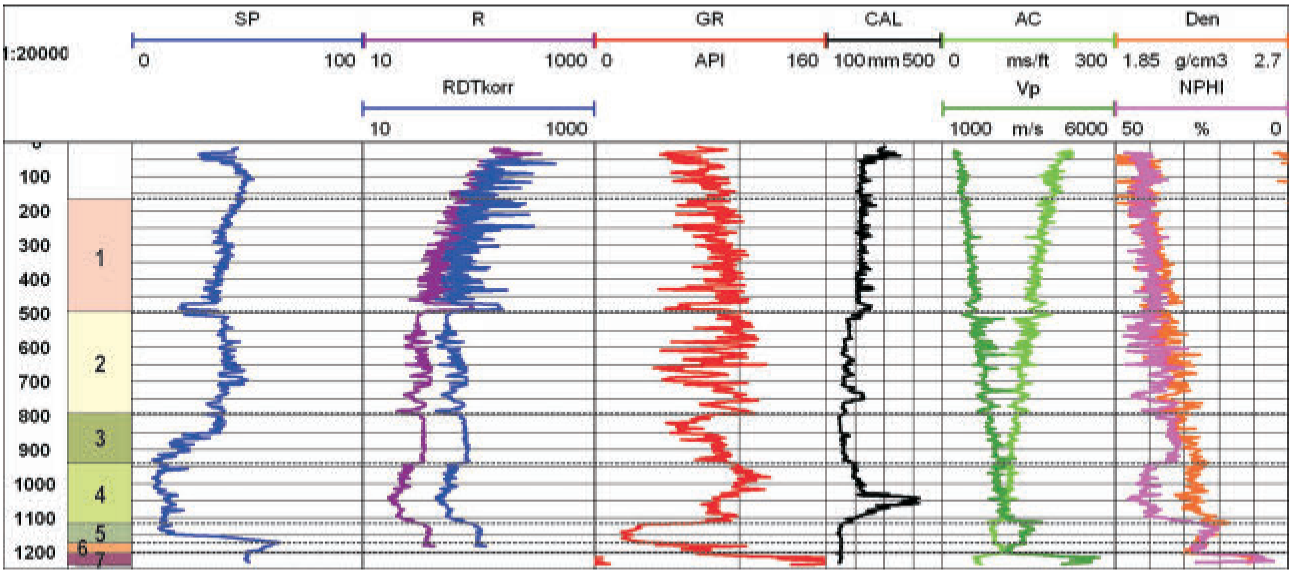


Figure 4.4.7. Geophysical well logs of the Battonya Bat-Észak-5 well

Legend: SP: spontaneous potential, R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log; AC: acoustic profile; Vp: acoustic velocity; DEN: density; NPHI: neutron-porosity log. *Geological column:* 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Szolnok Fm (Lower Pannonian), 4. Endrőd Fm (Lower Pannonian), 5. Endrőd Fm Tótkomlós Calcareous Marl Member (Lower Pannonian), 6. Middle Miocene, pre-Pannonian, 7. Variscan basement rocks

Csanádalberti North (Csanádalberti-Észak). Two dissolved gas containing (undersaturated) oil reservoirs are known in the Mesozoic carbonate basement and the overlying Badenian clastic, lithothamnium limestone, as well as in Lower Pannonian calcareous marl, which were discovered by the Csal-É–1 and –2 wells, in 1991 and 1992. The basement reservoir situated in an OWC depth of 2,298 m bsl stores intermediate type oil, with a density of 868 kg/m^3, the dissolved gas content is 170 m^3/m^3. The combustible part of the gas is 36.6%, the calorific value 15.3 MJ/m^3, CH_4 32.1%, CO_2 54.5%, N_2 8.9%, C_{5+} 13 g/m^3. The other reservoir is located in Lower Pannonian calcareous marl in a depth of 2,224 m bsl, the density of the paraffinic oil is 828 kg/m^3, the dissolved gas content is 140 m^3/m^3. Quality parameters of the dissolved gas are identical with those of the basement reservoir.

Csanádapáca. Four reservoirs are known in the field on the north-east flank of the Battonya–Pusztaföldvár High in depths of 1,848 and 955 m bsl, which were explored by the Csa–2 (1968) and Csa–3 (1975) wells. The lowest reservoir in the *Békés horizon* contains undersaturated oil in the Middle Triassic dolomite, dolomite breccia and in the overlying Lower Pannonian conglomerate–sandstone succession. The density of the paraffinic oil is 840 kg/m^3, the dissolved gas content 83 m^3/m^3, the calorific value 6.5 MJ/m^3. The CH_4 content is 13.7%, CO_2 81.3%, N_2 3.1%, the C_{5+} content is 5 g/m^3, the oil holds hydrogen sulphide.

Two free gas reservoirs (A–I and A–II) are known in the *Földvár horizon* in Lower Pannonian clay-bearing sandstone reservoirs. The combustible part of the gas in reservoir A–I (GWC: 1,744 m bsl) is 88.6%, the calorific value is 39.3 MJ/m^3. The CH_4 content is 77.5%, CO_2 8.0%, N_2 3.4%, the C_{5+} is 52 g/m^3, contains hydrogen sulphide. The combustible part of the gas in reservoir A–II (GWI: 1,721.5 m bsl) is 91.8%, the calorific value is 36.4 MJ/m^3, CO_2 8.6%, N_2 0.6%, the C_{5+} 27 g/m^3, contains hydrogen sulphide.

The uppermost natural gas reservoir is in Upper Pannonian silty sandstone, at a GWC depth of 955 m bsl. The combustible part of the natural gas is 98.3%, the calorific value is 36.6 MJ/m^3. The CH_4 content of the gas is 94.7%, CO_2 1.7%, N_2 0%, C_{5+} 1 g/m^3, does not contain hydrogen sulphide.

Kaszaper South (Kaszaper-Dél). The discovery well was the Kasz-D–1 well drilled in 1971. Undersaturated oil reservoir was identified in the Lower Pannonian *Békés horizon*, in calcareous marl (OWC 1,541 m bsl). The density of the paraffinic oil is 861.1 kg/m^3, the dissolved gas content 52 m^3/m^3. The combustible part of the dissolved gas is 34%, the calorific value is 16.8 MJ/m^3, CH_4 29.4%, CO_2 62.5%, N_2 2.5%, C_{5+} 24 g/m^3.

Twenty-eight free gas reservoirs are identified in the Upper Pannonian sequence marked Pl2 A–W in silty sandstone reservoirs. The average the calorific value of the accumulated gas is 36.4 MJ/m^3.

Kevermes. A free gas reservoir was discovered by the Kev–2 well in the *Battonya horizon* in 1975. The gas accumulated in the Lower Pannonian fractured calcareous marl (Tótkomlós Calcareous Marl Member) its combustible part is 32% and the CO_2 is 65%. The GWC depth is 1,607 m bsl. The combustible part of the gas is 31.5%, the calorific value is 12.2 MJ/m^3, CH_4 29.4%, CO_2 65.3%, N_2 3.2%, C_{5+} 0.7 g/m^3.

Kunágota. The Kunágota Kág–2 well (2009) discovered six free gas reservoirs in Upper Pannonian sandstone layers at a depth of 891–938 GWC m bsl. The calorific value of the gas is 35.3–35.8 MJ/m^3, CH_4 96.9–98.2%, CO_2 0.7%, N_2 1.0–1.2%, the C_{5+} is 0.2–1.5 g/m^3.

Magyarbánhegyes, **Magyarbánhegyes South (-Dél), Magyarbánhegyes East (-Kelet)**. The Magyarbánhegyes Mbh–1 well discovered an undersaturated oil accumulation in Lower Pannonian calcareous marl (Tótkomlós Marl Mb) in 1989. The OWC is in a depth of 2,367 m bsl. The density of the intermediate oil is 818 kg/m^3, the dissolved gas content is 5 m^3/m^3, combustible part 96.2%, calorific value 36.1 MJ/m^3.

The Magyarbánhegyes South occurrence is a free gas reservoir containing 96.2% combustible gases in a Lower Pannonian reservoir discovered by the Mbh-D–1 well in 2010. The GWC is at 1,660 m bsl. The calorific value of the gas is 36.1 MJ/m^3. The undersaturated oil reservoir of the Magyarbánhegyes East occurrence was discovered in 2009 by the Mbh-K–1 well, in an OWC depth of 2,053 m. The reservoir rock is siliceous shale of the pre-Cenozoic basement and the overlying calcareous marl (Tótkomlós Marl). The density of the paraffinic oil is 818 kg/m^3, the dissolved gas content is 49 m^3/m^3. The combustible part of the dissolved gas is 56.1%, the calorific value 30.0 MJ/m^3, CH_4 40.9%, CO_2 38.3%, N_2 5.6%, C_{5+} 84 g/m^3. It contains hydrogen sulphide.

Magyardombegyház South-west (Magyardombegyház-Délnyugat). The wells Domb-DNy–4 (1989), Domb-DNy–7 (2008), Domb-DNy–8 (2009) discovered free gas reservoirs. The Pl1mm reservoir is in Lower Pannonian calcareous marl (Tótkomlós Marl), the GWC is at a depth of 1,196 m bsl. The combustible part of the natural gas is 35.5%, the calorific value is 13.8 MJ/m^3, CH_4 32.9%, CO_2 62.2%, N_2 2.4%, the C_{5+} 5 g/m^3. The Pl2–1/c8 is a free gas reservoir situated in Upper Pannonian sandstone (837 m bsl GWC), the combustible part is 98.1%, the calorific value is 35.4 MJ/m^3. CH_4 content 97.7%, CO_2 0.2%, N_2 1.7%. The gas quality of the free gas reservoir Pl2–1/c with condensate (801.5 m bsl) is identical with the former.

Figure 4.4.8 presents geophysical well logs typical for the area.

Medgyesbodzás. Undersaturated oil reservoir is known in Middle Miocene sandstone and in the directly overlying Lower Pannonian calcareous marl (Tótkomlós Marl) discovered by the Med–4 well in 1996. The OWC is in a depth of 2,344.5 m bsl. The density of the intermediate oil is 845.0 kg/m^3. The combustible part of the dissolved gas is 78.2%, the calorific value is 39.2 MJ/m^3. The CH_4 content is 57.2%, the CO_2 21.3%, N_2 0.5%, the C_{5+} 74 g/m^3.

Medgyesegyháza. The Medgyes–2 well discovered one undersaturated oil reservoir and one free gas reservoir in 1989. The oil reservoir is found in Lower Pannonian calcareous marl reservoir, the OWC is in a depth of 2,599 m bsl. The density of the paraffinic-intermediate type oil is 812 kg/m^3, dissolved gas content 5 m^3/m^3, combustible part of the gas 44%, calorific value 22.8 MJ/m^3, CH_4 30.2%, CO_2 52.4%, N_2 3.1%. The free gas reservoir is in Upper Pannonian sandstone (GWC: 1,215 m bsl), the combustible part is 98.2%, the calorific value is 36.5 MJ/m^3. The CH_4 content is 94.7%, CO_2 0%, N_2 1.7%.

Mezőhegyes. The Mezőhegyes Mh–1–3 (1960–61), Mh–5–8 (1962–63), Mh–20 (1974), Végegyháza Vég–2 (1961) and Dombegyháza Domb-DNy–5 (1989) wells discovered two oil reservoirs with gas cap and a number of free gas reservoirs.

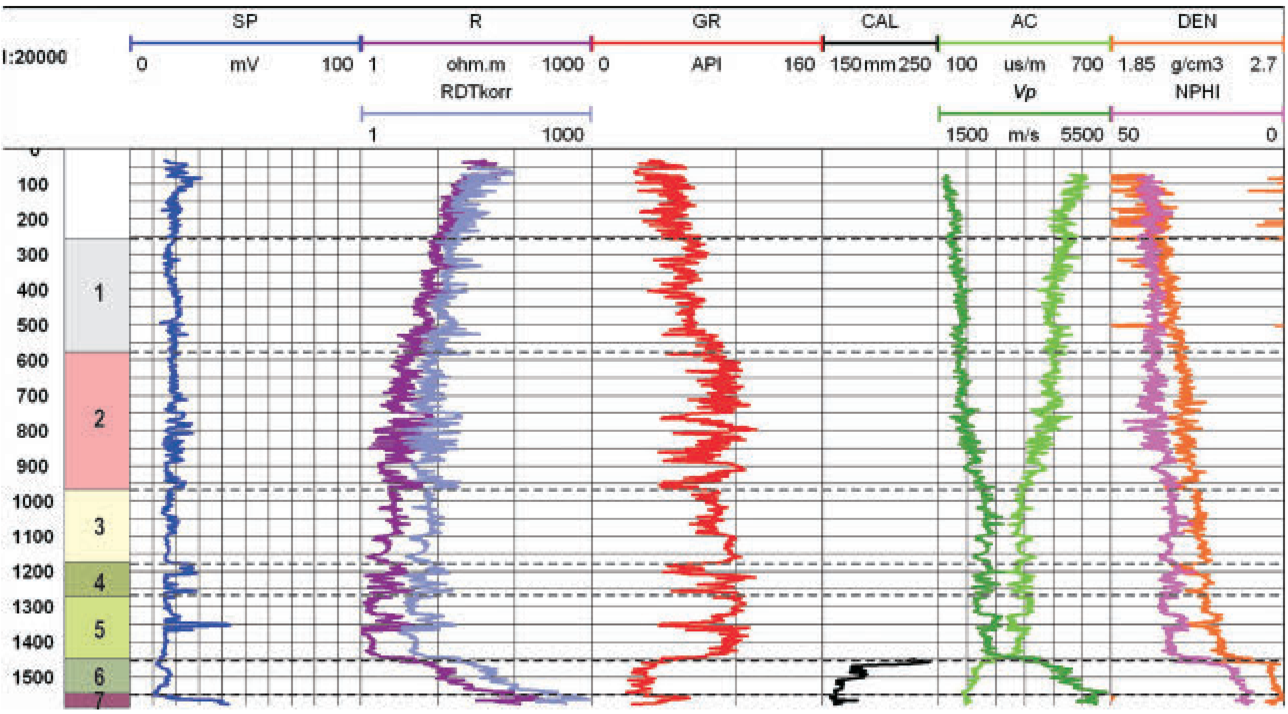


Figure 4.4.8. Geophysical well logs of the Magyardombegyház Domb.SW-6 well

Legend: SP: spontaneous potential, R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log; AC: acoustic profile; Vp: acoustic velocity; DEN: density; NPHI: neutron-porosity log. *Geological column:* 1. Nagyalföld Fm (Upper Pannonian), 2. Zagyva and Újfalu Fm (Upper Pannonian), 3. Algyő Fm (Lower Pannonian), 4. Szolnok Fm (Lower Pannonian), 5. Endrőd Fm (Lower Pannonian), 6. Endrőd Fm Tótkomlós Calcareous Marl Member (Lower Pannonian), 7. Variscan basement

The Batt–1 and –2 oil reservoirs are located in the so-called *Battonya horizon*, in Lower Pannonian basal conglomerate (Békés Conglomerate Fm), the oil is of paraffinic type. The OWC depth of the Batt–1 reservoir is at 1,094 m bsl, the oil density is 830 kg/m^3, the dissolved gas contents 73 m^3/m^3, the combustible part of the gas is 43.9%, the calorific value is 18.4 MJ/m^3, CH_4 39.2%, CO_2 52.6%, N_2 3.5%, the C_{5+} is 0 g/m^3. The Batt–2 reservoir (OWC 1068 m bsl) oil has a density of 836 kg/m^3, parameters of its dissolved gas are similar to that of the Batt–1 reservoir.

Three free gas reservoirs are known in the Lower Pannonian succession. The GWC depth of the Batt–3 reservoir is 1,057 m bsl, it is in the *Battonya horizon,* in calcareous marl reservoir (Tótkomlós Calcareous Marl Mb), the gas is identical with that of the Batt–1 reservoir. The calorific value of the gas in the two additional Lower Pannonian reservoirs situated in silty sandstone-reservoir rock (918 and 937 m bsl GWC, respectively) is 34.4 MJ/m^3, CH_4 95.9%, CO_2 0%, N_2 4.1%, the C_{5+} is 0 g/m^3.

Nineteen additional free gas reservoirs are discovered in Upper Pannonian silty sandstone and sandstone reservoirs in a pseudoanticline dome, lithologically closed traps. The GWC depth is between 457 m and 719 m bsl. The calorific value of the natural gases is 30.8 MJ/m^3 in the two reservoirs explored by the Domb-DNy–5 well, CH_4 content 85.6%, CO_2 0.2%, N_2 14.0%. The calorific value of the gas in the other reservoirs is 34.6–36.1 MJ/m^3, CH_4 content 93.3–98.3%, CO_2 0–0.9%, N_2 1.3–4.2%, the C_{5+} 0–3 is g/m^3.

Mezőhegyes South-east (Mezőhegyes-Délkelet). The Mh-DK–1 well discovered two free gas reservoirs in 2010 in the neighbourhood of the Battonya North field, in the line of the Battonya–Pusztaföldvár High ridge. Reservoirs are situated in Lower Pannonian sandstone, the GWC is 640 and 677 m bsl. The calorific value of the natural gases is 35.1–35.3 MJ/m^3, CH_4 content 97.4–98.4%, CO_2 0.1%, N_2 1.5–2.2%, the C_{5+} is 0 g/m^3.

Mezőhegyes West (Mezőhegyes-Nyugat). The occurrence was discovered by the Mh-Ny–1 and Mh-Ny–2 wells in 1990. It is divided into two field sections in the south-western flank of the Battonya–Pusztaföldvár basement high ridge. Wells Mh-Ny–1, –3, –4 were drilled in the eastern and Mh-Ny–2 and –8 in the western part of the field.

In the western field section undersaturated oil reservoir was identified in Lower Pannonian calcareous marl (Tótkomlós Marl Mb) (OWC at 1,442 m bsl). The density of the paraffinic type oil it 808.8 kg/m^3, the dissolved gas content is 50 m^3/m^3. The calorific value of the gas is 35 MJ/m^3. No data are available for the compounds.

Eight free gas reservoirs were identified in the two field sections, five reservoirs in Lower Pannonian sandstone (GWC in 995–1,084 m bsl, Algyő Formation), three reservoirs in Upper Pannonian sandstones (779–1,011 m GWC). The calorific value of the gas in the reservoirs is 34.9–36.8 MJ/m^3, CH_4 84.1–97.9%, CO_2 0.5–0.9%, N_2 6.1–7.3%, the C_{5+} is 11– 21 g/m^3.

Nagybánhegyes. Two reservoirs are known in the two field section drilled by the Nbh–1 and –2 wells in 1988 and in 1989. The reservoir formed in Mesozoic basement rocks and the overlying Lower Pannonian basal calcareous marl (Tótkomlós Marl Mb) stores undersaturated oil, the OWC can be found in a depth of 1,656 m bsl. The density of the intermediate type oil is 872.0 kg/m^3. The dissolved gas content is 42 m^3/m^3, the calorific value is 14.7 MJ/m^3, CH_4 27.7%, CO_2 49.8%, N_2 16.9%, the C_{5+} is 16 g/m^3.

The Upper Pannonian sandstone (GWC at 740 m bsl) holds free gas reservoir, the combustible part of the gas is 59.8%, CH_4 54.9%, CO_2 36.5%, N_2 3.7%, the C_{5+} 2 g/m^3. Its calorific value is 23.3 MJ/m^3.

Pitvaros North (Pitvaros-Észak). The Pit-É–1 well (1991) discovered two undersaturated oil reservoirs (OWC 1,806 and 1,730 m bsl) in Lower Pannonian calcareous marl (Tótkomlós Marl Mb). The lower reservoir is formed in the top zone of Middle Miocene rocks and in the directly overlying basal calcareous marl, the upper one is a stratigraphically and lithologically closed trap, also in calcareous marl. The oil is of the paraffinic type in both reservoirs. Density of the oil in the lower reservoir is 836.7 kg/m^3, dissolved gas contents 70 m^3/m^3, the calorific value is 22.0 MJ/m^3, CH_4 content 32.1%, CO_2 56.5%, N_2 1.7%, the C_{5+} 111 g/m^3. The oil in the upper reservoir is of a density of 807 kg/m^3, it contain 20 m^3/m^3 dissolved gas, the calorific value is 30.9 MJ/m^3. The CH_4 content is 67.6%, CO_2 2.1%, N_2 3.2%, the C_{5+} is 9 g/m^3.

Pusztaföldvár. The field was discovered by the Pusztaföldvár Pf–1 well in 1958. The discovery wells and the other exploration wells explored a total of 46 reservoirs. Reservoirs were divided into four lesser units or reservoir horizons based on the accumulated fluids and the lithostratigraphical position of the reservoir location, and they were provided with separate names and numbering (FÁBIÁN et al. 1975, 4.4.9). The horizons:

— *Békés horizon*: the lowest reservoir in the field, richest in hydrocarbons (OWC depth is 1,688 m bsl). It is a mixed (combustible and inert) gas containing oil reservoir with a large-scale gas cap. The reservoir rocks are Lower Pannonian coarse clastics, sandstone, conglomerate and marl overlying directly the basin basement unconformity. The oil is of the paraffinic type, its density is 875 kg/m^3, the dissolved gas content is 82.5 m^3/m^3. The dissolved gas and the cap gas are high inert containing combustible mixed gases, the combustible part is merely 30.9%. The CH_4 content of the gas is 27.8%, CO_2 65.4%, 3.7% nitrogen-dioxide is present, the C_{5+} content is 14 g/m^3.

— *Földvár-alsó (Földvár Lower) horizon*: three undersaturated oil reservoirs (Földvár-A–I/a, –I.,–II., OWC 1,628–1,640 m bsl) and one wet gas reservoir (Földvár-A–III., GWC depth is 1,602 m bsl) explored in the north-western part of the structure in Lower Pannonian silty sandstone belong to this horizon. The reservoirs are entrapped in a pseudoanticline structure, combined with lithological closure. The oil is of the intermediate type, their density is 870–875 kg/m^3, the dissolved gas content is 34–42 m^3/m^3. The natural gas is wet gas, containing incombustible (inert) components in low percentage only (CO_2 4–6%, N_2 3–4%). The methane content in the dissolved gas is 80–88%. The C_{5+} content is 13–50

g/m³. The hydrogen sulphide-content is high, 5–58 mg/m³. The combustible part of the free gas is 93%, the calorific value is 39 MJ/m³.

— *Földvár-felső (Földvár Upper) horizon*: three major (Földvár-A–1, –2, –3, GWC 1,507–1,545 m bsl) and three lesser (Földvár- B–1, –2, –3, GWC 1,430–1,503 m bsl) natural gas reservoirs were discovered in Lower Pannonian silty sandstones with high calorific value wet gas. The reservoir fluids entrapped in lithologic traps of a pseudoanticline dome. The gas composition of the natural gas reservoirs is identical with that of the lower-horizon gas, with a calorific value of 35–38 MJ/m³, the hydrogen-sulphide content are low.

— *Puszta horizon*: a total of 35 small scale or greater natural gas reservoirs (Puszta–A, –B and –C series) were discovered in Upper Pannonian sand–sandstone layers in a depth of 800–1,250 m bsl, with gas consisting predominantly of methane. Dry gases were accumulated in the lens form lithologic traps of the pseudoanticline structure, consisting of 96–98% of methane. The CO_2 and N_2 content together account for about 3–4%, the hydrogen-sulphide content is 0.3–1.5 mg/m³, minimum amount.

During the exploration of the field — due to a technical error of the Pf–50 well — part of the cap gas of the Békés horizon oil reservoir, about 1 billion m³ gas was transmigrated into the near surface Upper Pannonian layers at a depth of around 300 to 500 m bsl, where secondary accumulations, the so-called stray gas reservoirs were formed.

The initial fluid pressure of the reservoirs is hydrostatic, no overpressure could be measured in any of the sites. The geothermal gradient in the field is bigger than the national average, 0.0655 °C/m (15.38 m/°C reciprocal gradient) (Fábián et al. 1975).

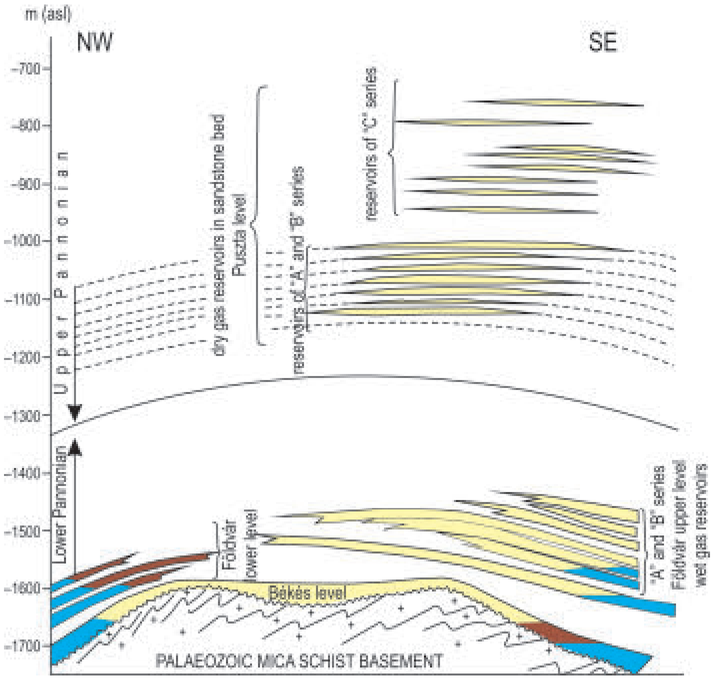


Figure 4.4.9. The position of the reservoir horizons in the Pusztaföldvár field (adapted from Fábián 1975)

Pusztaföldvár North (Pusztaföldvár-Észak). Two free gas reservoirs were discovered by the Pf-É–1 well in 1991 in Lower Pannonian sandstone, the GWC is in a depth of 2,112 and 2,134 m bsl. The combustible part of the natural gas accumulated is 92.1 and 93.6%, the calorific value is 44.3 and 42.0 MJ/m³, CH_4 78.5 and 81.9%, CO_2 4.7 and 4.9%, N_2 3.1 and 1.5%. The gas of the reservoirs contains 162, and 82 g/m³ gas condensates.

Pusztaszőlős. The Pusztaszőlős oil and natural gas field was discovered in 1960 by the Psz–1 well. One oil reservoir with gas cap and 20 free gas reservoirs are known in the field. Reservoirs were divided into reservoir horizons based on the accumulated fluids and the lithostratigraphical position of the reservoir location, and they were provided with separate names and numbering. The trap types in the field are the stratigraphic trap along the basement unconformity and the combined structural/lithologic traps in the Neogene pseudoanticline structure. Reservoir horizons are as follows:

— *Szőlős horizon*: the reservoir horizon of the Mesozoic carbonate basement and the directly overlying Lower Pannonian basal conglomerate. It includes an oil reservoir with gas cap, the OWC depth is 1,677.5 m bsl. The oil is of the paraffinic type, its density is 875 kg/m³, the dissolved gas content is 62 m³/m³. The combustible part of the natural gas is 54.7%, the calorific value is 21.5 MJ/m³. The CH_4 content of the gas is 50.4%, CO_2 38.6%, N_2 6.7%, the C_{5+} is 3.7 g/m³.

— *Csanád horizon*: reservoir level of the Lower Pannonian sandstones. Two free gas reservoirs formed in the clay-bearing sandstones are known in this horizon, the GWC sits in 1,456 m bsl. The combustible part of the gas in the reservoirs is 94.1%, the calorific value is 35.0 MJ/m³. The CH_4 content is 91.3%, CO_2 1.5%, N_2 4.4%.

— *Komlós horizon*: the reservoir of the lower part of the Upper Pannonian strata, formed in sandstone. Reservoirs within the horizon were grouped in A, B and C series from the bottom to up and were numbered within the groups. Two reservoirs are known in the A, six reservoirs in the B, and 11 reservoirs in the C series, respectively. The combustible part of the gas in the A horizon (1,157 m bsl GWC) is 96%, the CH_4 content is 93%, CO_2 1%, N_2 3%. The depth of the reservoirs in the B series are 1,005 and 1,086 m bsl (GWC). The gases contain 97% methane, their CO_2 and N_2 content is 1–2%. Four reservoirs in the A and B series have been utilised as underground gas storage since the total production of the initial recoverable reserve. The depth of the reservoirs in the C series is 771 and 985 m bsl (OWC). The combustible part of the gas is 96%, the calorific value is 35–36 MJ/m³.

— *Puszta horizon*: sandstone beds of the upper part in the Upper Pannonian beds. No commercial reservoirs are on record in this horizon.

Tompapuszta *(in the area of the Battonya East field).* Seven free gas reservoirs were discovered by the Tompu–1 well in 2013 in a depth of 491 and 565 m bsl (GWC). The reservoir rock is Upper Pannonian sandstone. The CH_4 content of the gas is between 98.0–98.3%, the calorific value 33.4 MJ/m^3, CO_2 content 0.1–0.3%, nitrogen 1.4–1.7%.

Tótkomlós. The occurrence was discovered by the T–1 well in 1941, but the well blew out and has been deteriorated. Effective production of the field could have been possible only after the T–9 well was drilled and assessed in 1956. Natural gases were accumulated in combined structural/lithologic traps in the compaction dome structure. The identified reservoirs are classified to the following horizons:

— *Békés horizon*: high incombustible (inert) containing gas reservoir is situated in the Lower Pannonian basal conglomerate in a depth of 1,500 m bsl (GWC). The combustible part of the natural gas is 46.0%, the calorific value is 17.4 MJ/m^3. No data are available for the gas composition.

— *Komlós-alsó (Komlós-A, Komlós Lower) horizon*: four free gas reservoirs are known in the Komlós–A horizon in Lower Pannonian silty sandstone reservoirs. The GWC is at depth of 1,258 and 1,396 m bsl. The combustible part of the natural gas accumulated is 77–93%, the calorific value is around 35 MJ/m^3, the CH_4 content is 81–89%, CO_2 3–15%, N_2 5–8%. The C_{5+} content in the lowest reservoir is 23 g/m^3.

— *Komlós-felső (Komlós-F, Komlós Upper) horizon*: 20 reservoirs were identified in the Komlós–F horizon. The reservoir rock is Upper Pannonian clay-bearing sandstone. The depth of the reservoirs is between 672 and 1,003 m bsl GWC. The combustible part of the gases is 92%, the calorific value is about 35 MJ/m^3.

Tótkomlós South (Tótkomlós-Dél). The T-D–1 well discovered the undersaturated oil reservoir in the Middle Triassic basement and the directly overlying Lower Pannonian calcareous marl in lithologic trap in 1991. The OWC depth of the reservoir is at 1,563 m bsl. The density of the accumulated paraffinic oil is 851 kg/m^3. The oil contains 70 m^3/m^3 dissolved gas. The mixed gas has as low calorific value as 17.5 MJ/m^3, the CH_4 is 30.3%, CO_2 60.3%, N_2 1.4%, the C_{5+} content is 15 g/m^3.

Tótkomlós South-west (Tótkomlós-DNy). The undersaturated oil reservoir situated in the Lower Pannonian calcareous marl (Tótkomlós Marl Mb) was discovered by the T–21 well in 1966. The OWC depth is 1,826 m bsl. The density of the paraffinic oil is 840 kg/m^3, the dissolved gas content is 50 m^3/m^3. The combustible part of the gas is 40.3%, the calorific value is 15.7 MJ/m^3, the CH_4 content is 39.2%, CO_2 58.3%, N_2 1.4%. It contains 16 g/m^3 condensate. The H_2S content of the gas is 46.7 mg/m^3.

Tótkomlós North (Tótkomlós-Észak). The single undersaturated oil reservoir was discovered by the T–I well in 1982. The OWC in the Lower Pannonian calcareous marl reservoir (Tótkomlós Marl Mb) is at a depth of 1,672 m bsl. The oil is of the intermediate type, its density is 869 kg/m^3. It contains 15 m^3/m^3 dissolved gas, the combustible part of which is 54%, the calorific value is 21.5 MJ/m^3. No data are available for the gas composition.

Tótkomlós East (Tótkomlós-Kelet). The T-K–1 well found this occurrence containing three free gas reservoirs in 1972. The depth of the lower reservoir situated in the *Békés horizon* is 1,672 m bsl (GWC), the reservoir rock is Lower Pannonian calcareous marl (Tótkomlós Marl Mb). The combustible part of the natural gas accumulated is 30.5%, the calorific value is 12.9 MJ/m^3. The CH_4 content is 26.5%, CO_2 57.6%, N_2 11.9%. The gas contains 12 g/m^3 condensate. Additional two free gas reservoirs were identified in Upper Pannonian silty sandstone, the reservoirs depth is 747 and 806 m bsl (GWC). The combustible part of the gas in the reservoirs is 98.3%, the calorific value is 36.4 MJ/m^3. The CH_4 content is 95.1– 95.3%, CO_2 0.5–0.7%, the nitrogen 1.0–1.1%.

Végegyháza West (Végegyháza-Nyugat). The field was discovered by the Vég-Ny–1 well in 1985, and in 1989 the Vég-Ny–7 well identified a separated reservoir near the basement. The lowest reservoir in the field section explored by the Vég-Ny–1 well can be found in the north-western part of the field, in a depth of 1,445 m bsl (OWC). Undersaturated oil reservoir was identified here in fractured Mesozoic basement dolomite. The density of the paraffinic type oil is 861 kg/m^3, the dissolved gas content is 91 m^3/m^3. The gas has high inert content, the calorific value is low, merely 17.0 MJ/m^3. No data are available on the composition of the gas. A free gas reservoir is identified in the southern part of the field, also in basement dolomite (1,400 m bsl GWC), the combustible part of which is 41.8%, the calorific value is 17.1 MJ/m^3, CH_4 content 38.4%, CO_2 55.5%, N_2 2.8%, C_{5+} content 13 g/m^3.

Eight free gas reservoirs were discovered in Lower Pannonian sandstone in the *Komlós-alsó* (*Komlós Lower)* horizon in the depth range of 1,277.5–1,337 m bsl (GWC). The combustible part of the gases is 88–92%, their calorific values is 35–37 MJ/m^3. The CH_4 content is 79–87%, CO_2 1–7%, the nitrogen content 6–7%, the C_{5+} is 16–67 g/m^3.

Three additional free gas reservoirs were identified in the Upper Pannonian *Komlós-felső (Komlós Upper)* horizon, in silty sandstone in a depth of 900– 1,013 m bsl. The combustible part of the gases is 94%, the calorific value is 35–37 MJ/m^3. The CH_4 content is 88–89%, CO_2 1.5–2%, N_2 4–6%, the C_{5+} content is 5–6 g/m^3.

The Vég-Ny–7 well discovered combustible mixed gas reservoir on the top of the fractured Mesozoic carbonate basement and the directly overlying Lower Pannonian base calcareous marl (Tótkomlós Marl Mb, GWC: 1,475 m bsl). The combustible part of the gas is 68.6%, the calorific value is 25.8 MJ/m^3, CH_4 content 65.3%, CO_2 26%, N_2 5.4%, the C_{5+} content is 4 g/m^3.

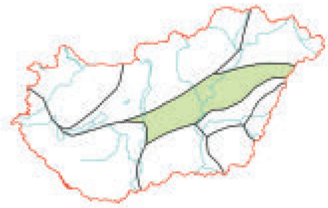
Békés Basin

Békés. The Békés–1 well discovered two free gas reservoirs in Lower Pannonian sandstone in the north-western part of the Békés Basin, north-east from the Battonya–Pusztaföldvár High. The GWC in the reservoirs is found in a depth of 2,448 and 2,906 m bsl. The combustible part of the gas is 94–96%, the calorific value is 38–40 MJ/m^3, the CH_4 content 84–87%, CO_2 3–5%, N_2 0.5–1%, condensate content 15 and 34 g/m^3.

Szabadkígyós *(unconventional occurrence).* The unconventional gas occurrence explored by the Szabadkígyós–1 (2009) well in the Békés Basin will be discussed in another chapter in this book dealing with the unconventional hydrocarbons.

Hydrocarbon exploration areas in Hungary — The northern part of the Nagykunság area with flysch basement

Edit Thamó-Bozsó



4.5

Exploration history

Crude oil and natural gas exploration started in the northern Tiszántúl after the First World War using surface methods of Ferenc Pávai-Vajna, due to the gas traces known from the dig out wells of the Hortobágy. However, these initial research efforts did not bring any substantial results, yet thermal waters were discovered (Kőrössy 1991). The Geophysical Institute applied the Eötvös torsion balance measurements for the purposes of geological explorations first in the world in 1917–20, suggested by Hugó Böckh, which showed gravity maximum at Hortobágy and Hajdúszoboszló. Drilling exploration started in 1918, and in the Hortobágy Hort–I well hot water with gas and oil traces occurred. The Vérvölgy well provided only a little amount of natural gas beside water in 1923–24. In the vicinity of Hajdúszoboszló and Karcag exploration wells were deepened from 1924 and 1927, respectively. The Geophysical Institute carried out seismic measurements in the area from 1936. From 1941 the Seismos company performed gravity measurements for MANÁT (Hungarian–German Mineral Oil Works Co), then Maszolaj (Hungarian–Soviet Oil) also started exploration from 1946, which was continued from 1954 by the Oil Exploration and Drilling Company, later by MAORT (Hungarian–American Oil Company), and from 1957 Oil Industry Trust and from 1960 OKGT (Hungarian Oil and Gas Trust) (Dank 1983). After 1991 mainly the Mol (Hungarian Oil and Gas Plc) explored the area. The key properties of the hydrocarbon accumulations identified up to 1985 are mainly contained in the work of Völgyi et al. (1985) and Juhász, Kummer ed. (1997).

The first discoveries of hydrocarbon occurrences in the area were made in the surrounding of Nádudvar and Szolnok in 1953. From this date almost all year was successful in terms of discoveries up to 1965, and a number of hydrocarbon reservoirs were discovered in the area of Rákóczifalva, Püspökladány, Kunmadaras, Törtel, Jászkarajenő, Kaba, Nagykőrös, Szandaszőlős, Kisújszállás East, Hajdúszoboszló, Ebes, Zagyvarékas, Túrkeve, Turgony, Tiszapüspöki, Karcag, Nagykörű and Cegléd. Among them, the Hajdúszoboszló natural gas field, identified in 1958, is an occurrence holding one of the largest gas resources in Hungary. The Kisújszállás West and the Fegyvernek natural gas fields were discovered in 1969, and the Abony, Újszilvás, and Kengyel fields followed suit in 1972, 1976, and in 1979, respectively. From the beginning of the 1980s up to the mid-1990s further occurrences were identified in the Penészlek, Tószeg, Besenyszög, Törökszentmiklós, Kengyel, Tiszagyenda, Egyek, Karcag, Szolnok and Kisújszállás area (Durda et al. 1995, Szentgyörgyiné et al. 1997c).

In the Szolnok exploration area, where nearly a hundred hydrocarbon and water exploration wells were deepened in the period between 1950 and 1980, exploration was made from the end of the 1990s by POGO Magyarország Ltd, later by its legal successor Toreador Hungary Ltd and the RAG Hungary Ltd. Natural gas accumulations were discovered in Örményes South-east and East area in 2003–2004, and in Kenderes South area in 2006 (Lemberkovics 2009, 2010; Lemberkovics, Csík 2010; Bates 2004). As part of the more recent investigations, 3D seismic surveys were also used. The Tiszakécske THL-Tik–1 well of Toreador Hungary Ltd (Toreador Magyarország Kft.) discovered a carbon dioxide reservoir in 2008. Geomega Ltd and PetroHungaria Ltd discovered natural gas accumulations between 2006 and 2010 in the Nyírség South area at Penészlek (Wórum et al. 2010). The wells of Magyar Horizon Energy Ltd marked HHE-Túrkeve-Nyugat, deepened in 2009 proved to be productive. Mol Hungarian Oil and Gas Company Plc discovered two natural gas occurrences in 2012 with the Tiszaszentimre Tiszi–2 well (Szentgyörgyiné et al. 2012c). A total of nearly 190 hydrocarbon reservoirs in 53 fields have been identified in the northern part of the Nagykunság area with flysch basement.

Geological overview

The area belongs to the Tisza Mega-unit and within it, the Mecsek Unit originating from the European plate and situated to the south from the Mid-Hungarian Fault Zone (Figure 2.3). The terrains and subterrains constituting the Tisza Mega-unit were united in the Variscan orogenic phase (Császár 2005). Due to the Variscan deformation, Barrow-type, amphibolite facies metamorphism took place some 330–350 million years ago (Árkai et al. 1985, Szederkényi 1998), and then low pressure Variscan heating led to granite formation about 270–330 years ago.

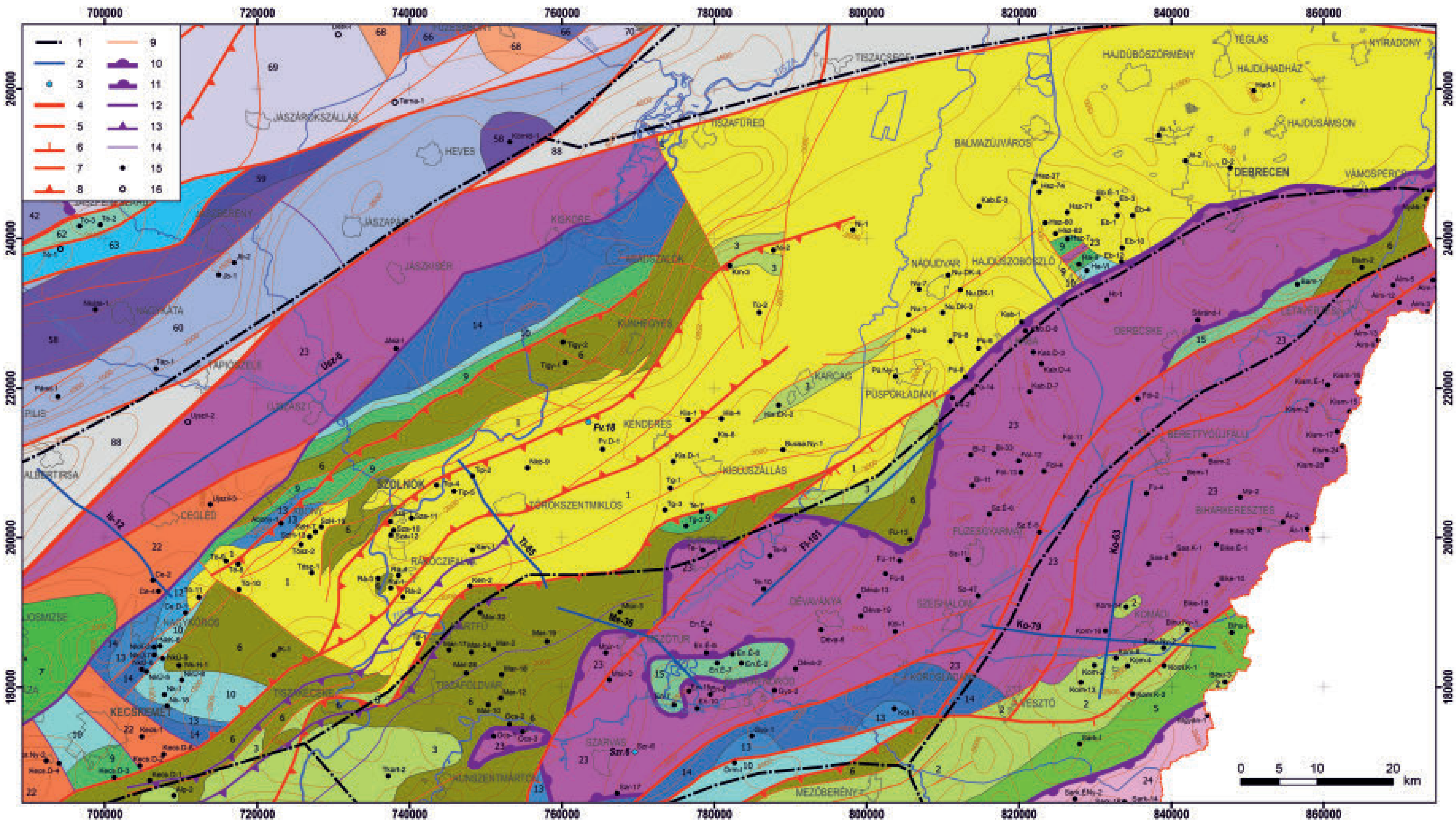


Figure 4.5.1. Pre-Cenozoic geological map of the Nagykunság area (HAAS et al. 2010)

Elements of legend: 1. boundary of the sub-basin, 2. trace lines of the sample 2D seismic sections in this book, 3. location of the well with geophysical logs (Figure 4.5.12. and 4.6.9.), 4. first-order Cenozoic tectonic line, 5. second-order Cenozoic tectonic line, 6. second-order Cenozoic normal fault, 7. second-order Cenozoic tectonic line, 8. second-order Cenozoic overthrust, 9. third-order Cenozoic tectonic line, 10. first-order Mesozoic nappe boundary, 11. first-order inferred Mesozoic nappe boundary, 12. second-order Mesozoic tectonic line, 13. second-order Mesozoic overthrust, 14. third-order Mesozoic tectonic line, 15. well hit the pre-Cenozoic basement, 16. well stopped above the pre-Cenozoic basement. *Legend for geological formations: 1.* Senonian–Palaeogene pelagic marls, flysch, 2. Senonian flysch, 3. Senonian terrestrial, shallow and deep-marine (bathyal) formations, 5. Lower Cretaceous platform facies limestone, 6. Lower Cretaceous basic volcanics and their redeposited marine sediments, 7. Lower Cretaceous pelagic marls, limestones, 9. Middle Jurassic – Lower Cretaceous pelagic limestones, cherty limestones, 10. Lower–Middle Jurassic pelagic fine-grained siliciclastic succession, 12. Upper Triassic – Lower Jurassic coal containing siliciclastic succession, 13. Middle Triassic shallow-marine siliciclastic and carbonate succession, 14. Lower Triassic fluvial and delta siliciclastic formations, 15. low grade metamorphic Mesozoic formations, 22. Variscan granitoid rocks, 23. Variscan metamorphites (gneiss, mica schist, amphibolite), 24. Variscan crystalline rocks without subdivision, 40. Upper Triassic – Lower Jurassic platform limestone, 42. Carnian–Norian platform dolomite, 58. Middle–Upper Triassic platform and basin carbonate succession, 59. Lower Triassic shallow-marine claystones, marls, limestones, 60. Upper Palaeozoic and Mesozoic formations without subdivision, 62. Jurassic basic magmatites, 63. Middle Jurassic olistostrome-melange, 65. Middle–Upper Triassic metavolcanics, 66. low grade metamorphic Middle–Upper Triassic platform carbonates, 67. very low grade metamorphic Middle–Upper Triassic slope and basin facies cherty limestones, 68. very low grade metamorphic Upper Permian – Lower Triassic shallow-marine limestones, sandstones, marls, 69. very low grade metamorphic Upper Palaeozoic and Mesozoic formations without subdivision, 70. very low grade metamorphic Upper Palaeozoic marine formations, 88. inadequately evaluable or unknown basement

The evolutional history of the area in the Mesozoic is associated with the northern shelf of the Tethys as part of the European continent and subsequently with the initial opening up of the Penninic Ocean in the Late Triassic (BUDAI, KONRÁD 2011).

In the beginning of the Late Cretaceous the Variscan metamorphic rocks of the Villány–Bihor Unit were folded up as a nappe from the south and south-west with a reverse fault onto the Mesozoic formations of the Mecsek Unit in the wake of a drastic compressions. The nappe boundary of the two units runs along the southern edge of the area with flysch basement.

The SW–NE direction arrangement of the main tectonic unit took place as a result of the nappe formation and imbrication (Figure 4.5.1). This series of tectonic events created narrow and steep ridges and in parallel between them deep-marine (bathyal) trenches, as well as a large basin in front of an arch, currently situated along the Szolnok– Máramaros-axis.

Basement formations

The pre-Cenozoic basement in the western and north-western part of the area (for instance Cegléd, Újszilvás, Kecskemét, Izsák and Solt regions) is formed of Variscan granitoids and higher grade metamorphic rocks in a depth of approximately 1,100–2,200 metres, which were sometimes reached by the wells below the flysch succession too. The SW–NE direction granitoid range of the Mórágy Complex is accompanied by medium grade metamorphic zones consisting mainly of gneiss, mica schist and amphibolite, which pop up on the surface around the Mecsek Mountains. The Mórágy Granite Formation which belongs to the Complex was generated by the mixing of magmas of varied composition, including monzogranite, monzonite, a variety of contaminated rock types and late-igneous leucocratic veins intersecting them. In the cooling phase following their intrusion they were subjected to greenschist facies regional metamorphism during the Variscan orogeny (BALLA, GYALOG ed. 2009). The radiometric (Rb–Sr and K–Ar) age of the granitoides is in the 330–350 million years range, the metamorphites are 322 million years old (SZEDERKÉNYI 1998), i.e. they are Carboniferous rocks.

The exploration wells drilled slaty sandstone, cherty shale, and siliceous shale as well, which are thought to belong to the Carboniferous Nagykőrös Sandstone Formation, subjected to old anchi-epizonal metamorphism. Reddish brown Permian arkose sandstone, and conglomerate beds overlie the metamorphites with unconformity here (KŐRÖSSY 1992).

In the Early Triassic, coarse-grained conglomerate, then refining upwards siliciclastic sediments, originating from the denudation of the surrounding elevated areas, deposited on the Variscan basement in fluvial and delta environments (BARABÁS, BARABÁS-STUHL 2005). They constitute the characteristic red, greyish-red, bluish-red coloured 60–380 m thick sequence of the Jakabhegy Sandstone Formation, which forms the basement in the Kecskemét–Nagykőrös and Kisköre areas (HAAS, BUDAI ed. 2014).

The red siltstone, red and green sandstone and green claystone layers of the Patacs Aleurolite Formation deposited in a tidal environment developed continuously on the shallow-marine ramp formed above the Early Triassic land in the wake of the Middle Triassic, Anisian transgression. They constitute the basement only in small extensions (for instance at Nagykőrös). The shallow-marine clastic sequence — containing more and more carbonate from bottom to top — is followed by the foliated, anhydrite-bearing marl, anhydrite-bearing dolomite and brecciated limestone beds of the Anisian Hetvehely Dolomite Formation which was deposited in a closed lagoon environment and already contains evaporitic formations (for instance in the Abony and Nagykőrös area).

The dark coloured, high organic matter containing marl, calcareous marl beds of the Kantavár Formation were deposited in closed lagoon environment at the end of the Middle Triassic (for instance at Nagykőrös). The black coal intercalations containing sandstone–siltstone–claystone sequence of the Mecsek Hard Coal Formation deposited in fluvial and delta paludal, and littoral paludal environment in the end of the Late Triassic and beginning of the Jurassic, which occurs in the Cegléd area in a small patch. The so-called "coal covering beds" of the Vasas Marl Formation consisting of sandstone, argillaceous marl, marl, calcareous marl layers in a thickness of 300–700 metres was formed somewhat later from the sediments deposited between the sublittoral and shallow bathyal environments. This formation occurs in several places, mainly in the Kecskemét–Nagykőrös area (BÉRCZINÉ MAKK 1998).

Transgression intensified in the course of the Early Jurassic and in its late phase the marly siltstone beds of the Óbánya Aleurolite Formation were generated in open-marine, shallow bathyal, anoxic conditions. The overlying beds include the open-marine, bathyal, Lower–Middle Jurassic Komló Calcareous Marl Formation and other pelitic Jurassic rocks which were formed under increasing water depths. They occur in a 20–240 metres thickness range for instance in the Hajdúszoboszló, Ebes, Tószeg, Turgony, Túrkeve, Törtel, Kunmadaras and Tiszagyenda areas in the wells (BÉRCZINÉ MAKK 1998).

During the Middle Jurassic – Lower Cretaceous, pelagic limestone and cherty limestone were formed (Óbánya Limestone, Fonyászó Limestone, Kisújbánya Limestone, and Márévár Limestone). They constitute the basement at the western edge of the area, for instance around Nagykőrös, and are known in the Tiszántúl at Tiszagyenda, Hajdúszoboszló and Ebes (BÉRCZINÉ MAKK 1998).

Pelagic clay marl and bentonitised basalt tuff (Hidasivölgy Marl Formation) as well as bedded crinoidal limestone (Apátvarasd Limestone Formation) were formed in the Early Cretaceous, which occur in the western part of the area at

Kerekegyháza, Lajosmizse, Nagykőrös, and in the Ebes region in the east. They can be found at Nagykőrös in a heavily tectonised and tectonically pinched position.

The products of the Lower Cretaceous submarine basic volcanism and the occasionally emerging subvolcanic formations are represented in the Mecsekjános Basalt Formation with its more than 300 metres total thickness. Its rock types consist of alkaline basalt, trachybasalt, tephrite and phonolite originating from picritic basalt magma (BILIK 1996). These rocks are the products of submarine rift volcanos, formed most probably in multiple stages, but it can be imagined that volcanism became younger within the zone towards the east (SZEPESHÁZY 1973). Volcanos and the atoll-type reefs formed on them denuded in the Early Cretaceous, and the resulting debris formed the hundreds of metres thick diverse, bathyal volcano-sedimentary and clastic sedimentary sequences of the Magyaregregy Conglomerate Formation (CSÁSZÁR 1998). At a distance from the volcanos, sandy marl sequences appeared in it on the slopes with tuffaceous marl and calcareous marl intercalations. These rocks are of considerable extension and they constitute the basement in the middle of the area mainly in the neighbourhood of the flysch zone, for instance in the environment of Jászkarajenő, Szolnok, Nagykőrös–Kecskemét, Tiszagyenda, but can also be found under the flysch for instance at Ebes.

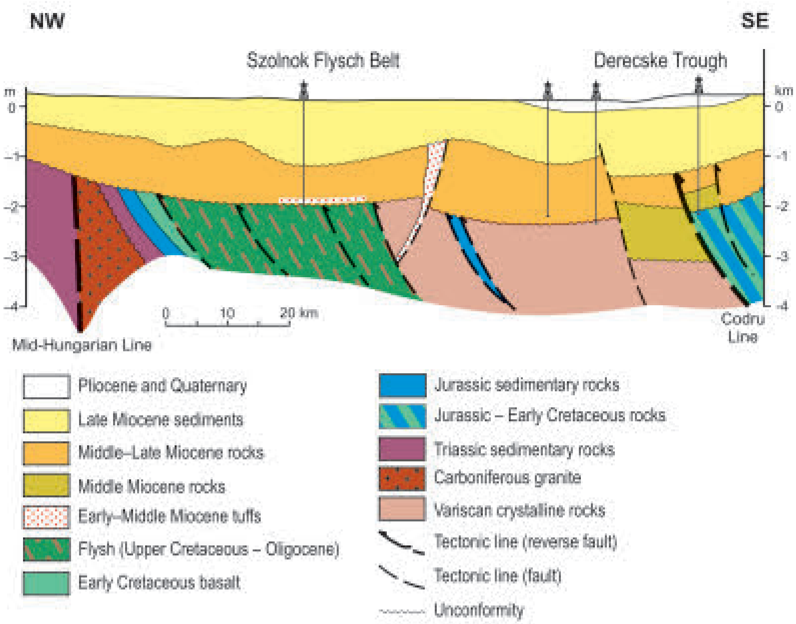


Figure 4.5.2. North-west-south-east direction section in the flysch basement area and its surrounding, adapted from SZEDERKÉNYI et al. (HAAS ed. 2012, p. 147)

In the beginning of the Late Cretaceous marls were formed in the basins with siliciclastic turbidite intercalations (Vékény Marl Formation) for instance in the Kerekegyháza area.

Substantial compression tectonic events took place in the Late Cretaceous with the formation of north-western vergence nappe systems with SW–NE strike (Figure 4.5.2). The tectonic evolution was followed by elevation and significant denudation, then the formations of the Senonian sedimentary cycle deposited onto the older Mesozoic (Triassic, Jurassic, Lower Cretaceous), eventually Variscan crystalline rocks of the denuded basement surface by erosion and angular unconformity. Their initial coarse-grained clastic terrestrial sediments are represented by the 20–180 metres thick Szank Formation, which was formed from the fragmentation of the bedrocks and was deposited in foot-slope environment, or following a short fluvial transportation, created alternating beds of poorly sorted breccia (conglomerate), then fluvial conglomerate, gravelly sandstone and greyish white sandstone (HAAS 1987). In the overlying strata red and grey calcareous marl, marl layers of the Izsák Marl Formation were deposited in the second part of the Senonian stage in the open-marine pelagic basin, far from the terrigenous source area (SZENTGYÖRGYI 1989). Its total thickness in the Izsák area is approximately 400 metres, in the Tiszántúl (Kunmadaras, Kisújszállás, Nádudvar) 60–300 metres.

Following the Senonian stage the western part of the area has emerged totally by the Palaeogene and has become dry land. At the same time the basement of the eastern part consists of "Szolnok flysch", which was deposited in pelagic environment, partly as turbidite sediments in the Senonian–Palaeogene.

The flysch is strongly tectonised, with 70–90° dip, and with imbricated structure. It runs in SW–NE direction in a length of about 150 km and in a wide of 20–30 km to the north-east from Szolnok (Törtel, Tószeg). The wells reached the flysch which was formed in several phases, most in a depth of 1,200 and 2,400 metres. Its actual thickness is not known, but on the basis of the seismic data it is must be minimum 1,000–1,500 metres. The older part of the flysch consists of the Debrecen Formation deposited in the Late Cretaceous on open-shelf above an intensively sinking bottom, set up of alternating layers of grey sandstone and silt (SZENTGYÖRGYI 1996a). The Debrecen Formation interfingers with the Izsák Marl Formation towards the west. Detailed nannoplankton analysis indicated substantial gaps in the sequence, most probably due to submarine erosion (BÁLDI-BEKE et al. 1981, NAGYMAROSY, BÁLDI-BEKE 1993, NAGYMAROSY 1998). The Palaeocene and Lower Eocene red, variegated and greenish grey coloured marl, claystone and sandstone-turbidite formations occur sporadically only in a few wells (BÁLDI-BEKE, NAGYMAROSY 1993, NAGYMAROSY 1998), the known extension of the Palaeocene formations is limited to the axial zone of the flysch belt. The Nádudvar Complex, formed in the Eocene and the Oligocene in deep-marine (bathyal) environment, consisting of the rhythmic alternation of silty marl and turbidite

sandstone containing grey and variegated thin sandstone layers, and coarser-grained sediments (gravelly sandstone, conglomerate, breccia). Oligocene flysch occurs mainly in the south-eastern edge of the flysch belt, in the strip running in the Püspökladány–Debrecen–Nagykároly direction in about 10–15 km, where it is created primarily by grey clay marl with sandstone intercalations (NAGYMAROSY in HAAS ed. 2012).

The pre-Cenozoic basement in the north-western part of the region is not known properly or is unknown.

Basin fill formations

A morphologically poorly accentuated surface was formed by the Neogene in the area as a result of the lifting and the subsequent remarkable erosion of the basement rocks. The evolution of the present structural regime of the region took place in the syn-rift phase of the Pannonian Basin which lasted from the Karpatian stage up to the Sarmatian stage (FODOR et al. 1999), when strongly differentiated subsidence was started in the area. The centres of sediment formation were shifted to the adjacent, intensively sinking deep basins (Derecske Trough, Jászság Basin, Mid-Hungarian-zone, Vésztő and Komádi–Mezősas Trough).

At the present time the surface of the Neogene basement runs mainly in a depth of approximately 2,000 metres, but it may reach a depth of as much as 5,500 metres in the Jászság Basin as well, while on the elevated areas it is situated in a depth of 500–1,500 metres (HAAS et al. 2010). The thickness of the Neogene succession varies between 2,000 and 3,000 metres in general, exceeding 3,000 metres only occasionally, while it does not reach even 1,000 metres above the elevated areas (ROYDEN, HORVÁTH 1988).

The wells identified Karpatian formations overlying the basement with a sedimentary gap only in a few locations such as at Törtel in a 76 m thickness (Tö–10 well). As a consequence of the syn-rift extension and as a result of the volcanism during the Karpatian and Early Badenian, thick volcanic beds were formed which have significant extension together with the intercalated Badenian sedimentary formations deposited in marine environment. The sedimentary rocks are represented mainly by clay, sandstone and conglomerate, in which volcanic material appears as well (SZENTGYÖRGYINÉ et al. 2012c). The volcanics can be classified as Tar Dacite Tuff Formation, Nagyhársas Andesite Formation, Mátra Volcanic Group, and Sátoraljaújhely Rhyolite Tuff Formation. The volcanic products consist partly of different varieties of acidic pyroclastic and lava rocks, complemented with redeposited tuff–tuffite types, which are frequently zeolitised. The piroxene andesite, agglomerate and tuff material of the Nagyhársas Andesite Formation (the so-called "Mátra Middle Andesite") are sometimes accompanied by rhyolite and dacite pyroclastic rocks. They appear in the area usually only in a couple of ten metres layers, except for instance the Balmazújváros Bal–3 well, where they have a more remarkable thickness (130 m). The total thickness of the Badenian volcanic rocks varied between 40 and 138 metres at Nádudvar and Püspökladány, being at least 230 m at Balmazújváros and 460 m at Lajosmizse. The coarse-grained clastic gravelly–sandy Abony Formation, formed on the Early Badenian abrasion seashore, appears as interfingering with volcanics or independently, and in the western part of the area the Badenian Clay Formation deposited in open-water basins. Above them the clastic succession of the Ebes Formation can also be found. The Szilágy Clay Marl Formation was formed during the Late Badenian in shallow neritic environment, which is constituted of 50–100 metres thick grey, foraminiferal clay marl with Turritella and Corbula. The lithothamnium- and molluscs-bearing sandstone of the Lajta Limestone Formation was formed from the material of the Late Badenian reefs, for instance in the neighbourhood of Nagykőrös and Cegléd.

The Hajdúszoboszló Formation — consisting of sandy, fine gravelly, bioclastic limestone, subordinated sandstone, marl and argillaceous marl intercalations — was deposited at the very beginning of the Sarmatian stage in brackish–shoreface–nearshore environment in a couple of 10 metres thickness (SZENTGYÖRGYI, HÁMOR 1997). Occasionally the Sarmatian Tinnye and Kozárd Formations also occur, sometimes they are interfingered. The Tinnye Formation, deposited in shoreface brackish water, is made up primarily of biogenic, eventually ooidic limestone and calcareous sandstone (the so-called "Sarmatian coarse limestone") containing mollusc-casts; the maximum thickness of the formation is 50–120 metres (HÁMOR, IVANCSICS 1997). The Kozárd Formation was deposited in shallow-marine – nearshore brackish water and consists of molluscs-bearing clay, argillaceous marl, subordinated sand, calcareous sandstone (the so-called "Cerithium-bearing limestone") and calcareous marl, the thickness of the formation is 100–150 m (HÁMOR 1997). The succession formed in the Sarmatian stage are missing in many places, or are present as erosional remnants mostly in limited geographic extension, for instance in the Püspökladány, Kaba, Nádudvar, Tatárülés–Kunmadaras, Balmazújváros, Budaábrány and Nyírábrány regions. A part of the tuff intercalations on the western part of the area can be classified in the Tokaj Volcanic Group.

During the post-rift phase, taking place from the Late Miocene, significant thermal subsidence occurred, locally with reverse faults of NE–SW strike (FODOR et al. 1999). The first sediments of the Lake Pannon formed some 12 million years ago in isolation from the world ocean (KÁZMÉR 1990, MAGYAR et al. 1999) are represented by material of the Endrőd Marl Formation, deposited in the innermost part of the basin, far from the source areas of the lake under diverse water depths varying from a couple of metres up to several hundred metres, in a so-called "starved basin". The sequence starts usually with basal marl, calcareous marl, marl layers of the Tótkomlós Calcareous Marl Member, and shifts gradually into the deep-water (hemipelagic) Nagykörű Clay Marl Member upwards (JUHÁSZ 1994). The thickness of the Endrőd Marl Formation is larger in the western part of the area, reaching 250–270 metres at Kisújszállás and Nagykörű, 100 metres at Szolnok. The

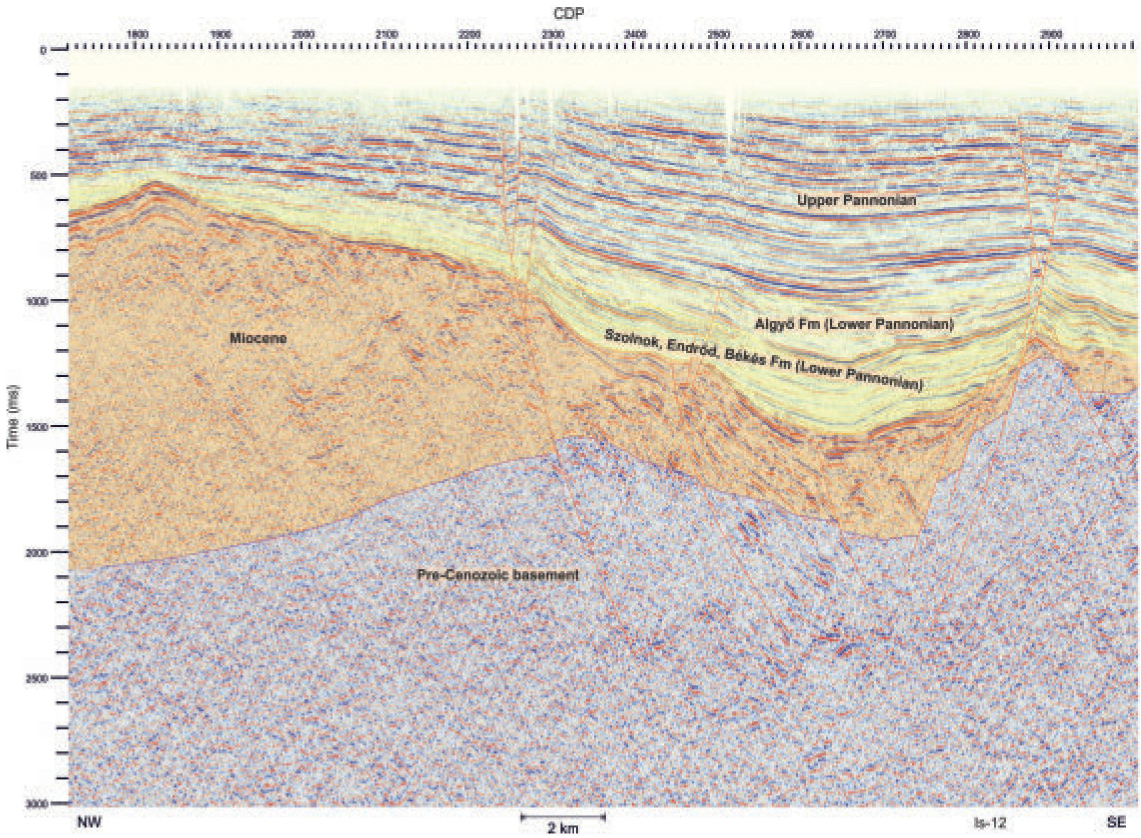


Figure 4.5.3. The Is–12 seismic section running in north-west–south-east direction (the trace line of the profile can be seen on Figure 4.5.1, the red lines indicate the faults)

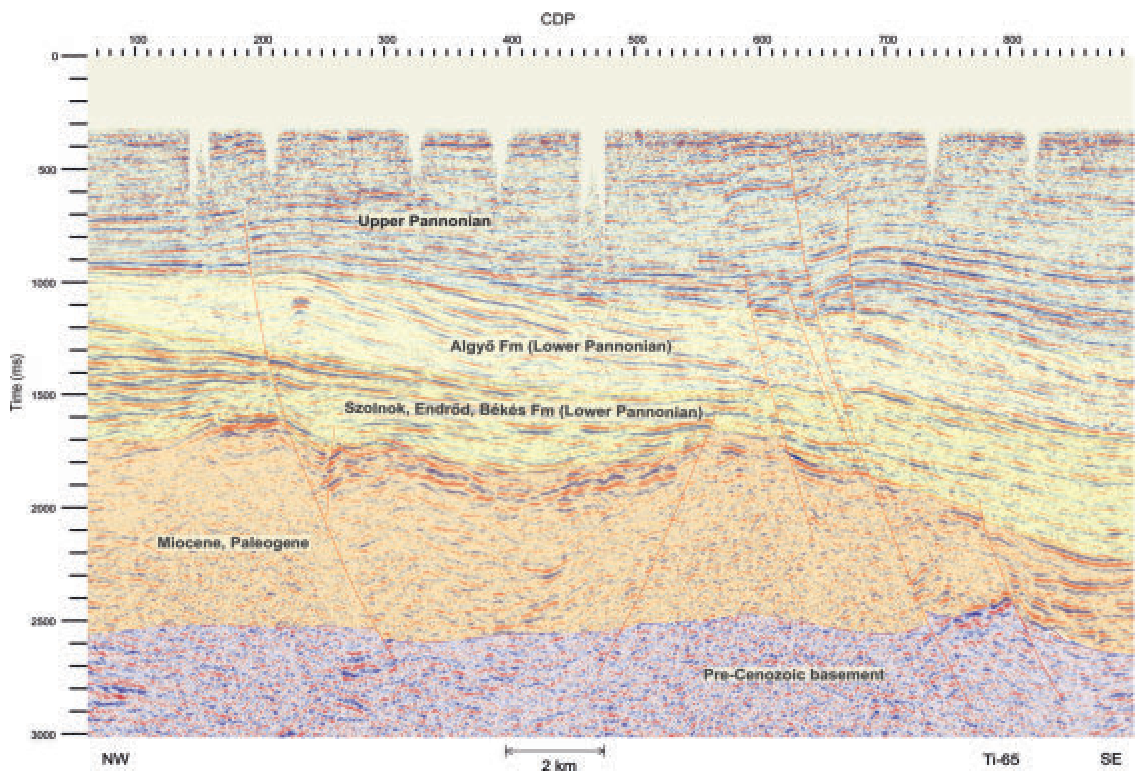


Figure 4.5.4. The Ti–65 seismic section running in north-west–south-east direction (the trace line of the profile can be seen on Figure 4.5.1, the red lines indicate the faults)

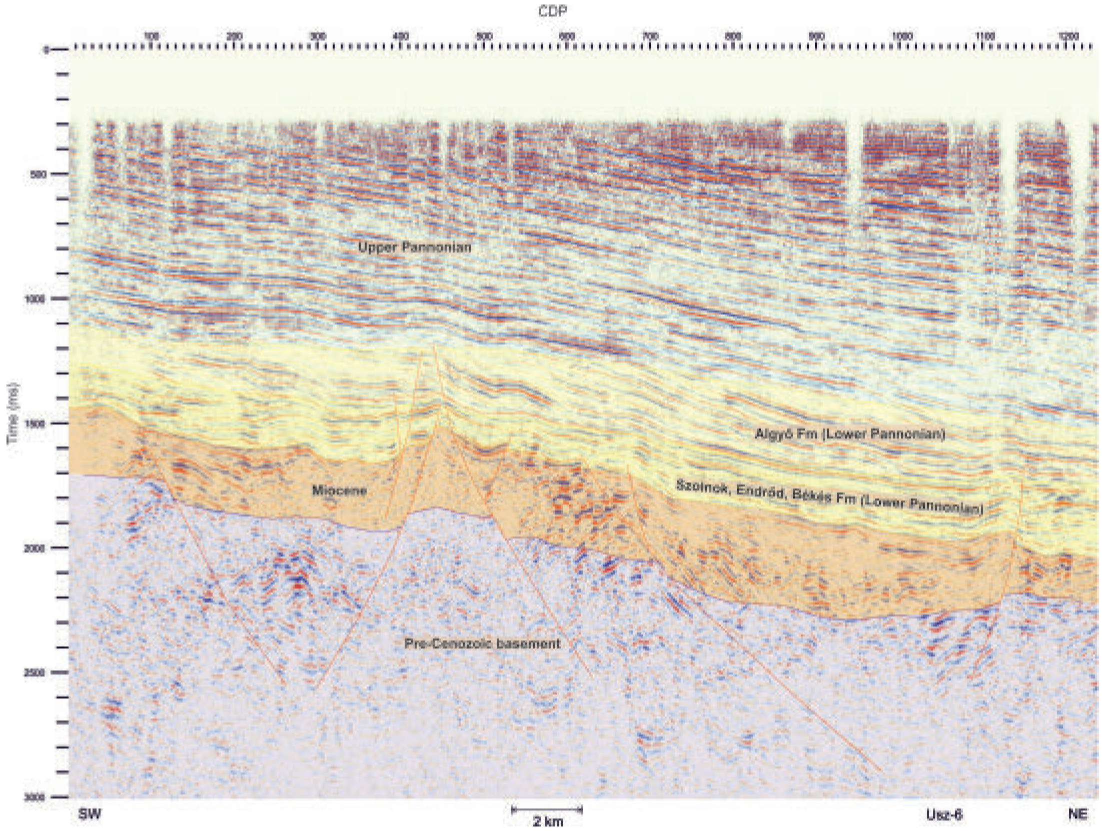


Figure 4.5.5. The Usz-6 seismic section running in south-west–north-east direction (the trace line of the profile can be seen on Figure 4.5.1, the red lines indicate the faults)

volcanics seen in the lowest layers of the formation are most probably classified in the Vizsoly Rhyolite Tuff Formation.

The filling up of the Lake Pannon in the eastern part of the Great Hungarian Plain took place from the NE (Vakarcs, Várnai 1991, Juhász 1992, Juhász et al. 2006). According to the results of the 3D seismic measurements the delta systems arrived initially from NE direction to the middle part of the area (for instance in the Karcag region), then the sediments coming from the north–north-west also reached the area, the two kinds of delta systems became interfingered, and finally the NE, or northern supply has become dominant (Szentgyörgyiné et al. 2012c).

The coarse clastics transported by turbidity currents into the deep basins from the edge of the sedimentary shelf formed at the rim of the Lake Pannon became the source material for the thick turbidite succession of the Szolnok Sandstone Formation (Figure 4.5.3–4.5.6). In the periods between turbidity currents pelite was deposited, into which fine sand bodies were intercalated in a thickness varying from 1–2 metres to 10–20 metres. The thickness of the formation may reach 1,000 metres in the deeper basins of the area, exceeding 800 metres at Tiszagyenda and

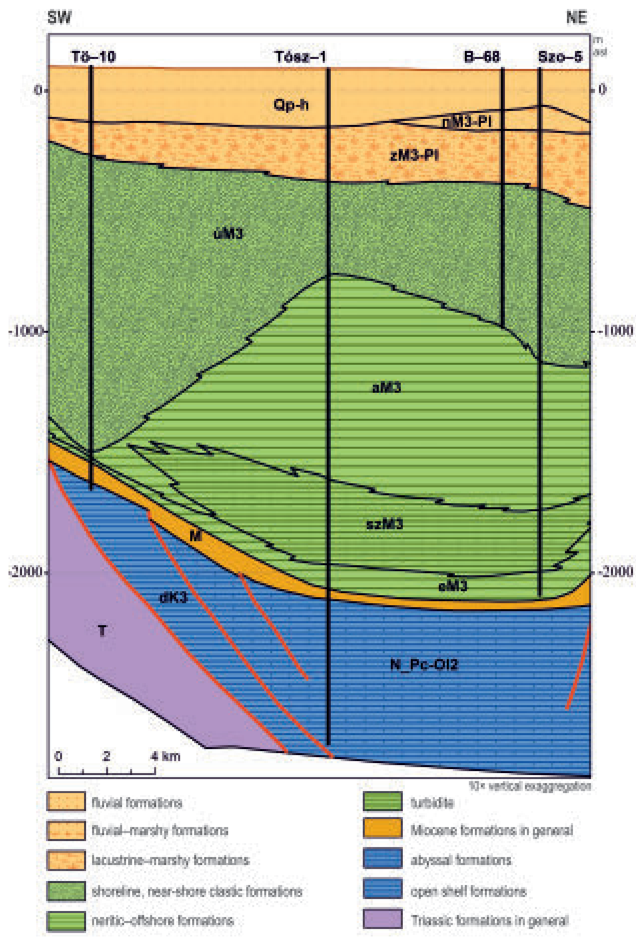


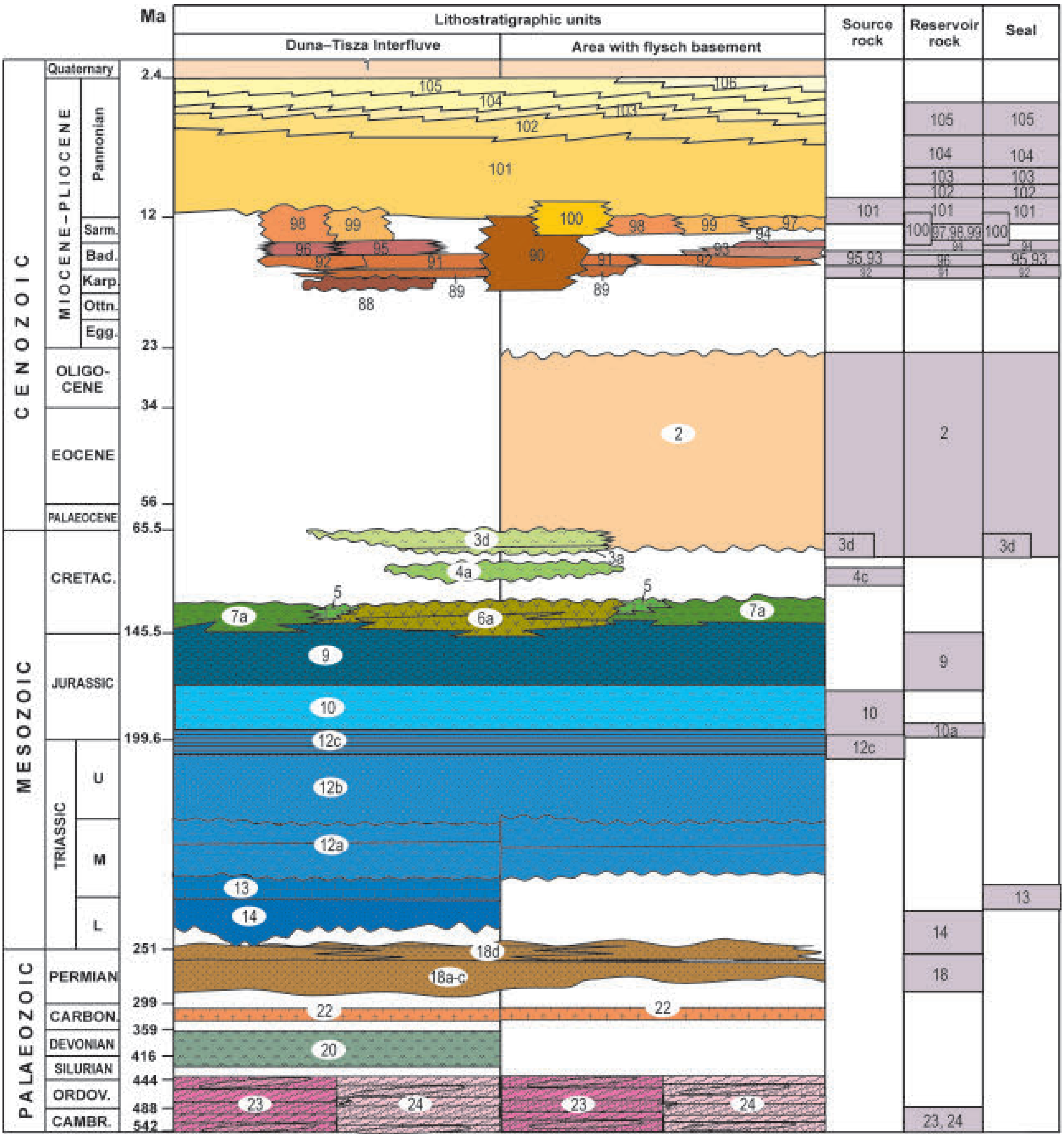
Figure 4.5.6. Geological section in SW-NE direction at the western end of the area with flysch basement

Legend: T: Triassic formations, dK3: Debrecen Formation, N-Pc-Ol2: Nádudvar Complex, M: Middle Miocene formations, eM3: Endrőd Marl Formation, szM3: Szolnok Sandstone Formation, aM3: Algyő Formation, úM3: Újfalu Sandstone Formation, zM3-Pl: Zagyva Formation, nM3-Pl: Nagyalföld Variegated Clay Formation, Qp-h: Pleistocene and Holocene formations

Besenyszög, and having an average thickness of approximately 400 metres in the areas with flysch basement, thinning out towards the edges.

An argillaceous marl and siltstone containing sequence of the Algyő Formation with sometimes thinner, sometimes thicker grey sandstone intercalations was deposited on delta slopes and on basin slopes, filling up the Lake Pannon. Its formation can be interpreted as infill of the sediment transport channels on the slopes. Due to the progradation of the slope the Algyő Formation is younger towards the south (VAKARCS 1997, MAGYAR 2009). The formation thickness reaches 620–850 metres in the vicinity of Tószeg, Szolnok, Balmazújváros and Nagykörű. Sometimes the Algyő Formation can be distinguished from the Endrőd Marl Formation only with some difficulty; therefore they are frequently merged in the drilling descriptions.

The sequence of the Újfalu Sandstone Formation consisting predominantly of the alternation of fine- and medium-grained sandstone, sand, aleurite and clay marl was deposited in delta front and delta plain environments of the shelf (in the morphological sense) of the Lake Pannon, and on coastal plains. Beside the abundant carbonised plant remnants lignite strata also appear in it frequently. Its thickness varies between 100 m and 1,200 m. The thicker sand layers deposited mostly as bars on the delta front, and as infills of delta lobes and as a series of point bars on the delta plains. The thinner sand bodies



formed by breaking of the levees during floods ("crevasse splays") and they are sand sheets of storms deposited in beach front environment. The finer-grained sediments of the formation (silt and clay layers), including palaeosoils and lignite strata, were deposited between the delta channels in paludal environment, on the flood plains and in smaller bays. The thickness of the formation in the area varies between 300 and 800 m in general.

The sediments of the Zagyva Formation were deposited in the background of the prograding deltas in fluvial–flood plain, lacustrine and paludal environments, which sometimes are difficult to distinguish from the Újfalu Formation. The Zagyva Formation consists of frequent alternations of grey–bluish-grey coloured silt – argillaceous marl – sandstone with variegated clay and lignite intercalations. Occasionally marl balls may also occur in it. The extremely diverse lithological structure depends on which part of the alluvial plain the sediments deposited.

Thinner and thicker sandy channel infills were also intercalated into the sedimentary sequence of the flood plains interrupted with clay-bearing aleurite containing flooding sand sheets. At other places only one or two thin sand layers are intercalated between the thick flood plain sediments. The deposition of the Zagyva Formation still began in the Late Miocene, and extended over to the Pliocene for a considerable part (GAJDOS, PAP 1996). Its thickness in the middle and eastern part of the area reaches occasionally 400–550 metres, thinner in the west (maximum 250 m). According to the integrated stratigraphic investigations the inversion of the basin started following the formation of the 6.8 million years old (Pa–4) sequence boundary (JUHÁSZ et al. 2006). The basin inversion was characterised in the area mostly by compression, which was not so strong as elsewhere due to the relatively large distance of the Adriatic plate colliding the lithosphere of the Carpathian–Pannonian region (BADA et al. 2007b). The sedimentary gap indicating the beginning of the inversion probably has been presented at the Miocene–Pliocene boundary (MAGYAR 2009). The Nagyalföld Variegated Clay Formation overlying the Zagyva Formation consists of alternating layers of bluish-grey sand and spotted, variegated clay, formed in lacustrine–fluvial environments with frequent lignite and gravelly sand layers, the deposition of which is thought to have been continued up to the beginning of the Pleistocene (GAJDOS, PAP 1996). It can hardly be distinguished from the Zagyva Formation both on the basis of the rock material in the wells and during the examination of the geophysical well logs, in spite of the fact that all in all lignite intercalations are more frequent in the Zagyva Formation (JÁMBOR 1989), while variegated clay appears more frequently in the Nagyalföld Formation (JUHÁSZ 1998). The average thickness of the Nagyalföld Variegated Clay Formation in the area with flysch basement is approximately 300 m, thinner towards the west (for instance only 57 metres thick at Kerekegyháza).

The tectonic events completed by the beginning of the Quaternary resulted in the morphological accentuation of the Carpathian Basin, the fragmentation of certain areas and the strong erosion of the elevated areas. The Pleistocene formations consist mainly of the sedimentary sequence of fluvial sand, gravelly sand, gravel, clay, and infusion loess, with 5–15, occasionally 30 m thick eolian sand intercalations in the Nyírség, and a few metres loess and fossil soil layers in the Hajdúhát. The thickness of the Pleistocene fluvial succession exceeds 200 metres in the Törtel, Szolnok, Kengyel, Nagykörű, Tiszagyenda areas, and 140 m in the Tószeg, Besenyszög and Püspökladány areas. The few metres thick Holocene succession is mainly set up of fluvial silt, sand, floodplain clay-bearing sediments, and soils formed on them, as well as paludal clay, peat, and still moving eolian sand mainly in the Nyírség and the part of the area in the Danube–Tisza Interfluve.

The transtensional stress field formed in the region during the Miocene still exists now in spite of the slowing down of the basin scale bottom subsidence, therefore the normal faults combined with lateral displacements practically reach the surface (BADA et al. 2007a). The schematic stratigraphic column and the elements of the hydrocarbon system of the northern Nagykunság area with flysch basement are presented on Figure 4.5.7.

An overview of hydrocarbon geology

Hydrocarbon accumulations in the area are situated in the NE–SW direction and mostly above the pre-Cenozoic basement elevations (Figure 4.5.8). The mixed gas belt of the middle part of the Great Hungarian Plain, partly with high inert containing gas accumulations locate on the area with flysch basement in the Tiszapüspöki–Nagykörű–Fegyvernek–Kisújszállás zone.

←**Figure 4.5.7.** Theoretical stratigraphic column and the elements of the hydrocarbon systems of the northern part of the Nagykunság area with flysch basement
Legend: 2. Senonian–Palaeogene flysch; 3a Senonian terrestrial, fluvial conglomerate, breccia; 3d Senonian deep-marine (bathyal) marl; 4c Upper Jurassic basin facies marl; 5. Lower Cretaceous shallow bathyal limestone; 6a Lower Cretaceous basic volcanics; 6b marine sediments redeposited from Lower Cretaceous basic volcanites; 7. Lower Cretaceous pelagic marl, limestone; 9. Middle Jurassic – Lower Cretaceous pelagic limestone, cherty limestone; 10a Lower Jurassic pelagic marl; 10b Lower Jurassic shallow bathyal, anoxic siltstone, marl; 10c. Middle Jurassic lagoon facies marl; 12a Middle–Upper Triassic bituminous limestone, calcareous marl deposited in brackish water lagoons; 12b Upper Triassic fluvial, delta, lacustrine siliciclastic succession; 12c Upper Triassic – Lower Jurassic fluvial, coastal succession with coal; 13. Middle Triassic shallow-marine, siliciclastic and carbonate succession; 14. Lower Triassic fluvial and delta siliciclastic formations; 18a–c Permian terrestrial, fluvial and lacustrine clastic succession; 18d Upper Permian – Lower Triassic fluvial clastic succession; 20. Lower Palaeozoic low grade metamorphic rocks; 22. Variscan granitoid rocks; 23. Variscan metamorphites (gneiss, mica schist, amphibolite); 24. Variscan crystalline rocks without subdivision; 88. Karpatian sedimentary formations; 89. Karpatian, mainly airfall dacite tuff; 90. Andesite, pyroclastite, rhyolite and dacite tuff; 91. Lower Badenian abrasion basal breccia; 92. Badenian open-marine clay, clay marl; 93. Badenian pelagic clay marl, marl; 94. Badenian shallow-marine biogenic limestone; 95. Upper Badenian open-marine clay, clay marl; 96. Upper Badenian shallow-marine, biogenic limestone, conglomerate; 97. Sarmatian shoreface, nearshore limestone, sandstone, marl; 98. Sarmatian coarse limestone, sand and gravel, deposited in shallow-marine, oligohaline salt-water; 99. Sarmatian shallow-marine clay, clay marl; 100. Badenian–Sarmatian andesite, dacite, rhyolite and tuff stratovolcanic succession; 101. Pannonian open-water lacustrine calcareous marl, marl, clay marl; 102. Pannonian sediments with deep-water turbidite origin; 103. Pannonian sediments deposited in underwater slope environment; 104. Pannonian siliciclastic succession deposited on delta front, and delta plain; 105. Pannonian fluvial and lacustrine siliciclastic succession; 106. Pannonian fluvial siliciclastic succession; 107. Quaternary sediments

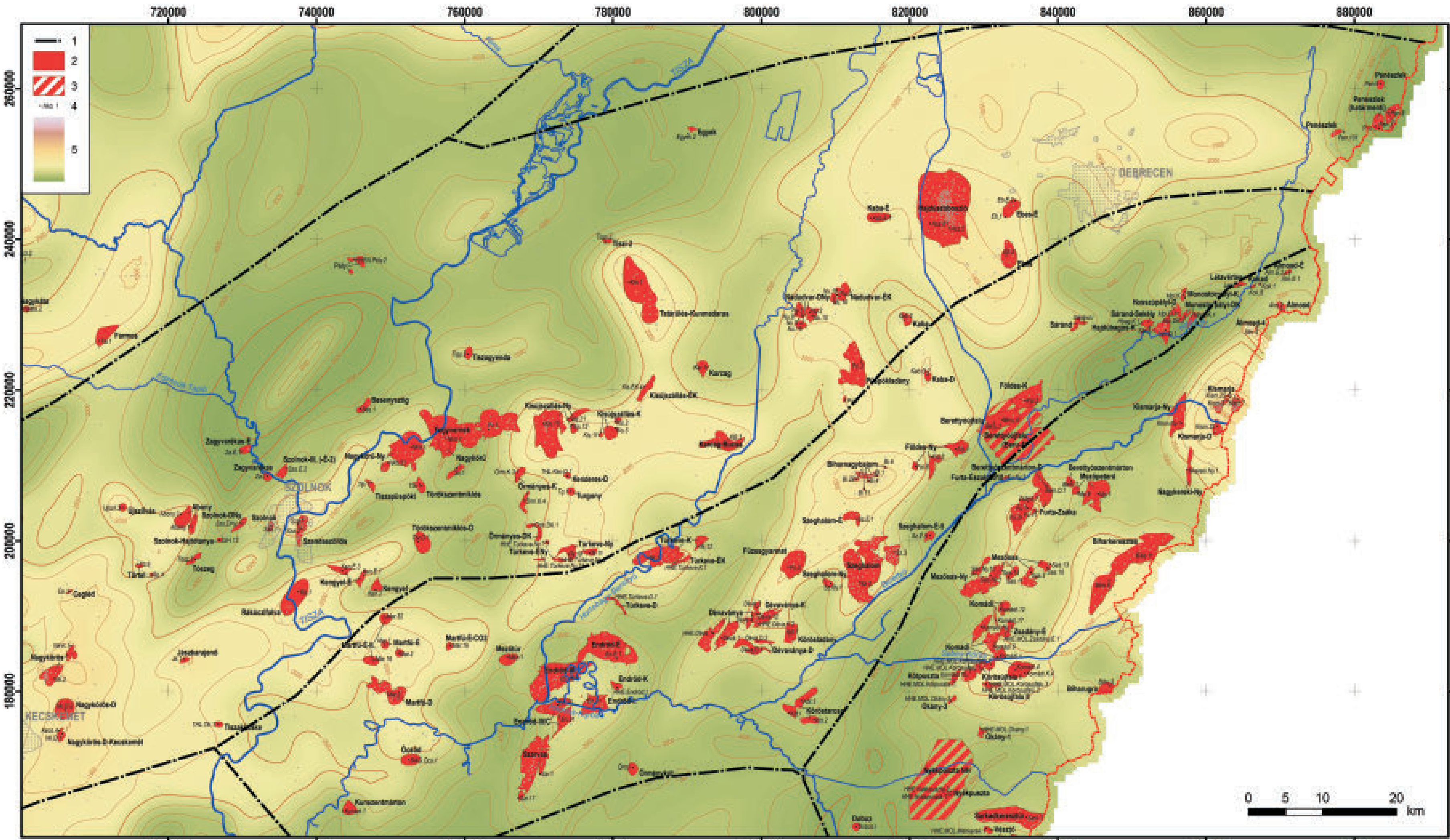


Figure 4.5.8. Depth of the pre-Cenozoic basement in the northern part of the Nagykunság area with the flysch basement and the location of the hydrocarbon fields known in the area
Legend: 1. Boundary of the sub-basins; 2. Conventional hydrocarbon field, 3. Unconventional hydrocarbon mining plot; 4. Hydrocarbon-occurrence discovery well; 5. Depth of the pre-Cenozoic basement

Source rocks

Potential source rocks include in this area primarily pre-Pannonian Miocene and the Lower Pannonian pelites and high clay containing sandstones, but based on the geochemical analyses the hydrocarbon generating capability of the Upper Cretaceous – Palaeogene, and certain Mesozoic rocks can also be assumed.

The oldest potential source rocks are the Lower and Middle Jurassic pelitic formations (clay marl – marl succession) which played a role in the build-up of the pre-Cenozoic basement, in particular the high organic matter containing rocks suitable for oil generation. They were formed in the course of the anoxic event in the Toarcian stage. The general TOC level of the Lower Jurassic clay marl which sits in an average depth of 1,550–2,000 m at Nagykőrös is 0.62–0.96%, the average value of vitrinite reflectance which indicates maturity is R_0=0.79–0.84% (HATALYÁK et al. 2010). The Lower Jurassic formations are found at Ebes below 1,500 m, with a vitrinite reflectance value of 2.9–4.0%, while they sit deeper than 3,000 m at Tószeg and their R_0 is 1.4% (BADICS, VETŐ 2011). The extension and depth, as well as maturity of Lower Jurassic formations were published by BADICS, VETŐ 2012 (Figure 4.5.9).

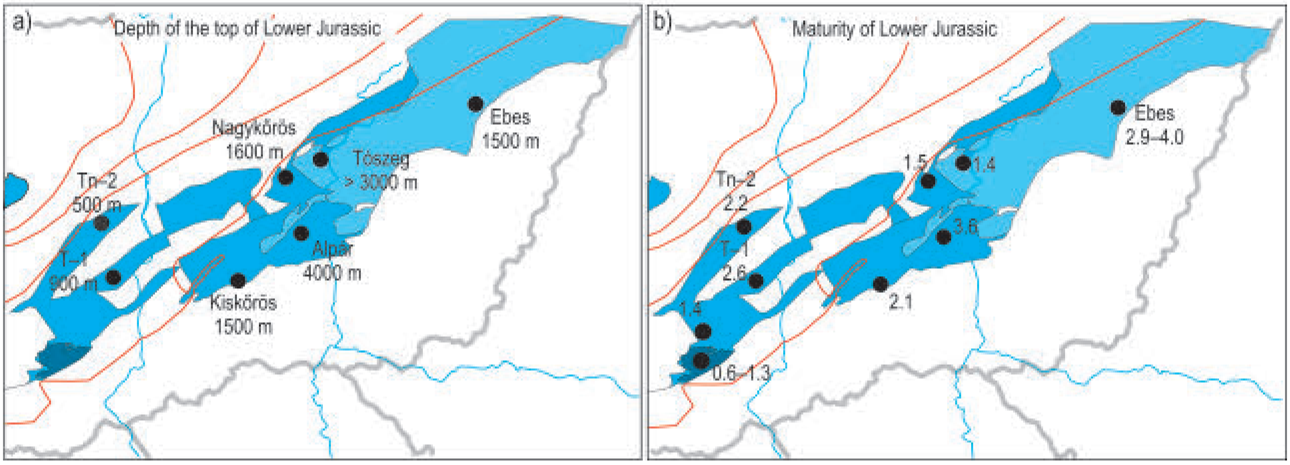


Figure 4.5.9. The extent and depth of the Lower Jurassic formations (A) and vitrinite reflectance data (B) adapted from BADICS, VETŐ (2012)

The Upper Cretaceous pelites hold mostly average organic carbon content and could generate gas, based on their vitrinite reflectance values they are in the last third of the oil generation zone. Certain parts of the Upper Cretaceous – Palaeogene flysch might have generated hydrocarbon as well (KÓKAI, POGÁCSÁS 1991). The C_{org} level is low in the Palaeocene pelites (5.12 mg/g), their bitumen content is autochthon and immobile, they are situated in the upper third of the oil zone, and their Type III organic matter might generate some gas. The Eocene formations hold low organic carbon and bitumen content, their R_0 value varies in a wide range, covering the entire oil generation zone (GAJDOS et al. 1997a). The Upper Cretaceous and Palaeogene pelites, marls, calcareous clays are potential source rocks at the northern edge of the Pannonian province in the Carpathian and Outer Carpathian flysch belt, which is indicated by the oil and source rock correlation and the biomarkers in the case of the Oligocene flysch succession (DOLTON 2006).

The pre-Pannonian Miocene pelites include very good (C_{org}>20 mg/g), good and acceptable formations from the point of view of hydrocarbon generation, but their CH-potential is low (<1). The high bitumen content of them occasionally definitely has allochthon origin. They contain gas generating Type III organic matter, and their thermal maturity corresponds to the beginning of the oil zone (GAJDOS et al. 1997a).

The organic carbon content (C_{org}) of the Badenian clay in the Nagykőrös Nk-Ú–1 well is 2.53 mg/g, the vitrinite reflectance (R_0) value is 1.13%. The TOC in the Sarmatian marl sample of the Kecs-Ny–1 well is 0.85%, the vitrinite reflectance is 0.74% (HATALYÁK et al. 2010). The Middle–Upper Miocene source rocks extension and maturity can be seen on Figure 4.5.10 as adapted from BADICS, VETŐ (2012).

Among the Lower Pannonian pelites half of the basal marls and calcareous marls has acceptable (5–10 mg/g C_{org}), and good (10–20 mg/g C_{org}) organic carbon content, their HC-potential (HI) reaches the 5 mg hydrocarbon / g of rock value. Their thermal maturity corresponds to the top of the oil zone (GAJDOS et al. 1997a, c). These successions belong to the Endrőd Marl Formation, and within it mostly to the Tótkomlós Calcareous Marl Member, which was deposited under anoxic conditions, very favourable for the purposes of preserving the organic matter. Its TOC value is 2–5%, and contains mainly Type III kerogen, with occasional enrichment of Type II kerogen generating oil. The organic carbon content (C_{org}) of the Lower Pannonian clay marl in the Nagykőrös Nk-Ú–1 well is 19.54 mg/g, the vitrinite reflectance (R_0) level is 0.57%. The high organic matter content marls (Makó Member) held formerly as Badenian and classified later into the bottom of the

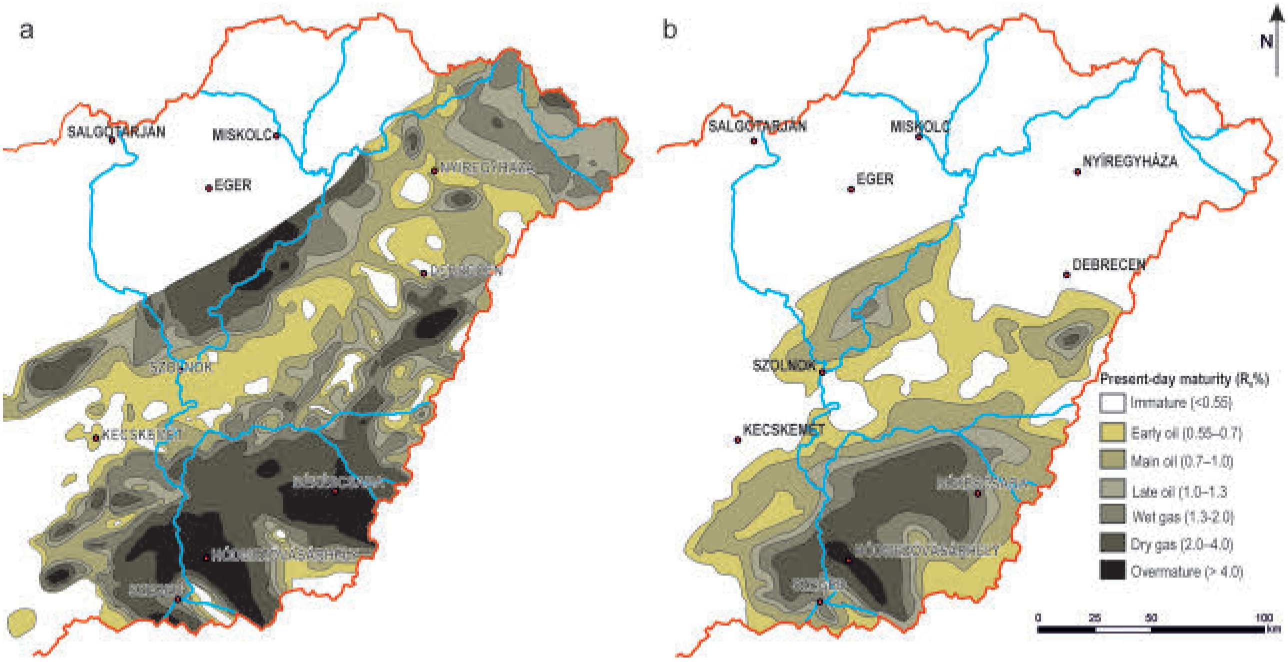


Figure 4.5.10. Extent and maturity of the Miocene source rocks of the Great Hungarian Plain, Base Middle Miocene (a) and Base Upper Miocene (b) adapted from Badics, Vető (2012)

Pannonian (Badics et al. 2011) were formed under open-water conditions and might have generated oil and gas from their mixed type II–III organic matter. Their TOC level is 1–1.5%, and they are currently in mature state in the Szolnok area, therefore might have generated a substantial amount of hydrocarbon.

All in all the Middle Miocene and the Lower Pannonian pelites are the most favourable source rocks, the thermal maturity of which corresponding to the oil generation zone could have been resulted from the heating up during the Neogene.

Hydrocarbon generation could have started in the flysch as early as in the beginning of the Palaeogene. The resulting hydrocarbons migrated away mostly, or were perished before the Miocene sediment formation would have been started, but the high volume flysch mass might easily generate dry methane under the oil window up to date (Jámbor 2012b).

The place of origin of the hydrocarbons on the area with flysch basement is questionable. According to certain opinions they might have come from the Liassic carbonaceous succession of the Jászság Basin (Fedor 2003) which has not been explored yet, but are assumed to exist, and from the Pannonian pelites of the Jászság Basin (Erdei et al. 1997a). The source rocks of a part of the natural gas is assumed to be the pre-Pannonian Miocene and Lower Pannonian formations in the south (Fedor 2003) in the deep zones of the Békés Basin (Gajdos et al. 1997a, d, Szentgyörgyiné et al. 1997c), but the natural gases might almost have been formed locally as well (Gajdos et al. 1997a).

Migration

The hydrocarbons generated and still generating due to subsidence and maturation migrated and migrate along the boundaries of the mineral grains and along the bedding planes towards mainly the pseudoanticlines where hydrocarbon accumulations could have formed in the rocks with appropriate porosity bordered by pelitic cap rocks. Upwards migration, as well as lateral migration, is substantial along the joints, faults and unconformity surfaces intersecting the Neogene–Quaternary formations (Jámbor 2012a–b). While the stratigraphic units and surfaces, primarily fourth- and third-order sequence boundary surfaces are important in the lateral migration, vertical migration takes place primarily along the fault planes of the fault systems, which however might also impede migration when they become impermeable (Szentgyörgyiné et al. 2012c). The sequence boundaries within the Pannonian formations might play an important role in migration, for instance those above and below the Újfalu Sandstone Formation. The flysch is to be seen as unfavourable in terms of migration (Benkő et al. 1996, Gajdos et al. 1997c).

The high inert containing and inhomogeneous composition gases of the mixed gas belt in the middle part of the Great Hungarian Plain migrated partly from the Jászság Basin into the area with flysch basement according to Fedor (2003), and probably were mixed with CO_2 gas of inorganic origin during the migration route. On the other hand, gases arrived here from southern direction, and displaced CO_2 from the reservoirs. The migration of upwards and to the east of the oil generated in the Jászság Basin is confirmed by certain geochemical data, but they do not provide any information on the migration direction of the gas component (Erdei et al. 1997a).

Based on the geochemical data according to the opinion of István Vető, the migration of three different gases of the Besenyszög – Tiszapüspöki – Fegyvernek South area (CH_4, N_2, CO_2) could have been independent from each other, and they mixed only at the trapping sites in the course of the multiple stage filling-up mechanism. The local carbon dioxide of basement origin migrated upwards and laterally into the Neogene formations along tectonic lines, and fault zones. The nitrogen got into the reservoirs most probably by migration in lateral direction. The combustible gas components are thought to have migrated from the south from the direction of the Békés Basin, because their migration here from the Jászság Basin is not confirmed, and the migration route is closed in north-western direction by the ridge running in the Szolnok–Kisújszállás line. The migration around Szolnok took place mainly along tectonic lines, and the combustible gases could have come first of all from southern direction (Gajdos et al. 1997b). The locally generated natural gases could have migrated vertically 0.8–2.2 km upwards. The mature, heavy oils of presumably Mesozoic origin found in Szolnok and its vicinity are thought to have filled up the Neogene traps by vertical migration (Gajdos et al. 1997a, Szentgyörgyiné et al. 1997c).

The seismic profiles at Penészlek suggest that the migration and the filling up of the reservoirs took place in the Upper Pannonian – Quaternary (Wórum et al. 2010).

Reservoir rocks

The key hydrocarbon reservoir rocks in the area are as follows:

— fractured, fragmented, cataclastic, brecciated parts of the Palaeozoic mica schist, gneiss and migmatite (Mórágy Complex, Mórágy Granite Formation, Körös Complex),

— Upper Permian – Lower Triassic arkose sandstone (Kővágószőlős Sandstone Formation, Jakabhegy Sandstone Formation),

— Lower Jurassic (Liassic) sandstone (for instance sandstone intercalations of Vasas Marl Formation),

— Mesozoic limestones (for instance Fonyászó, Kisújbánya and Márévár Limestone Formations),

— Upper Cretaceous – Palaeogene sandstone and conglomerate layers of the flysch, flysch-like sediments (Debrecen Formation, Nádudvar Complex),

— Middle Miocene (Badenian) conglomerate, breccia, sandstone, tuffaceous sandstone, calcareous sandstone, sandy marl (Abony Formation),

— Middle Miocene (Badenian) riodacite tuff, tuffite (Mátra Volcanic Group),

— Middle Miocene (Badenian) limestone (Lajta Limestone Formation, Ebes Formation),

— Middle Miocene (Sarmatian) sandstone, tuffaceous sandstone, calcareous sandstone, conglomerate, sandy marl (Hajdúszoboszló, Tinnye and Kozárd Formations),

— Middle Miocene (Sarmatian) fractured marl, calcareous marl, silty marl (Hajdúszoboszló and Kozárd Formations),

— Middle–Upper Miocene volcanics, for instance tuff, calcareous tuffite, zeolitised volcanics, volcanic agglomerate (Tokaj Volcanic Group),

— fractured parts of the Lower Pannonian basal calcareous marl, sandy calcareous marl (Endrőd Marl Formation, Tótkomlós Calcareous Marl Member),

— Lower Pannonian prodelta turbidite sandstone, aleurolitic sandstone, marly sandstone, clay-bearing sandstone (Szolnok Sandstone Formation),

— Lower Pannonian delta slope, basin slop sandstone, aleurite containing sandstone, clay-bearing sandstone (Algyő Formation),

— Upper Pannonian delta front and delta plain sandstone, aleurite containing, and clay-bearing sandstone, bar and channel filling facies sandstone (Újfalu Sandstone Formation),

— Upper Pannonian – Pliocene sandstone, aleurite containing, and clay-bearing sandstone (Zagyva Formation).

More than 60% of the hydrocarbon accumulations in the area have Lower Pannonian reservoir rocks. The Upper Pannonian sandstones are also important reservoirs, nearly a quarter of the occurrences was accumulated in them (for instance certain reservoirs of Ebes, Hajdúszoboszló, Kaba, Karcag–Bucsa, Nádudvar, Nagykőrös, Szandaszőlős, Törtel and Turgony fields). Roughly every tenth accumulation is situated in pre-Pannonian Miocene formations, mainly in Middle Miocene sandstone, tuffaceous sandstone, conglomerate (for instance in the Kengyel, Kisújszállás, Nádudvar, Nagykőrös, Örményes, Püspökladány and Tiszagyenda areas). At some places Miocene volcanics also act as reservoirs (for instance in the Karcag–Bucsa, Kisújszállás West and Penészlek fields). Upper Cretaceous – Palaeogene flysch reservoir rock occurs at Hajdúszoboszló and Püspökladány, partly Mesozoic limestone reservoir at Ebes and Nagykőrös, and in the latter field Permian sandstone also stores natural gas.

The greatest porosity reservoir rocks are the Pannonian sandstones (15–30%), in particular the Újfalu Sandstone Formation, because it is poorly consolidated, has lower cement content and less compacted than the older formations. The porosity is lower of the Badenian and Sarmatian reservoir rocks (10–20%) and of the Endrőd Marl Formation (3–8, sometimes 15%). The Palaeogene and Mesozoic formations, as well as the Palaeozoic metamorphites in general are characterised by a low porosity below 7%.

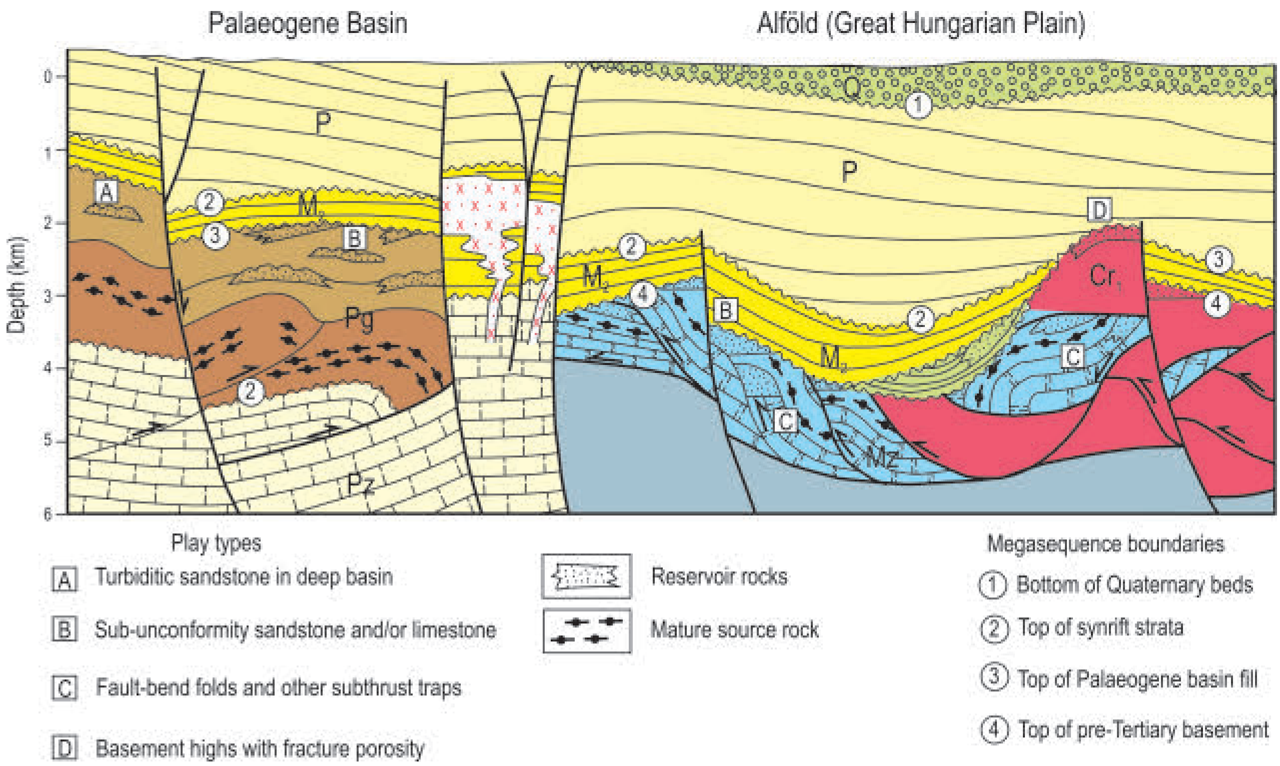


Figure 4.5.11. Theoretical profile of the hydrocarbon systems in the area and the wider surroundings (HORVÁTH, TARI 1999)

The idealised profile of the hydrocarbon systems in the area and the wider surroundings is shown on Figure 4.5.11 adapted from HORVÁTH, TARI (1999).

Seal rocks

The seal rocks of the reservoirs are made of poor permeability pelitic rocks. Among them, Lower Pannonian pelites, marls, calcareous marls form closure of the hydrocarbon accumulations in a great part of the area. Less frequently Upper Pannonian pelitic seal rocks may also occur, for instance in certain occurrences of the Törtel, Szandaszőlős, Hajdúszoboszló, Kaba South, Túrkeve West and Turgony fields. The seal rocks consisting of marl, argillaceous marl and clay layers of the Szolnok Sandstone Formation and the overlying Algyő Formation can be associated with maximum transgression events of various orders (SZENTGYÖRGYINÉ et al. 2012c). The 20–50 m thick argillaceous marl – clay layer belonging to the Pa–4 third-order sequence boundary behaves as a regional seal formation. Occasionally the clay-bearing parts of the flysch (for instance at Püspökladány) and the Upper Pliocene pelites (for instance at Ebes) provide closure. Seal rocks may also be the impermeable layers of the Miocene volcanic tuffs, tuffites and lava rocks locally.

Trapping

Hydrocarbons in the area accumulated primarily in stratigraphic/lithologic traps and combined structural–stratigraphic traps. Hydrocarbons migrating away along the joints, faults and unconformity surfaces accumulated mainly on morphological elevations, and in smaller or larger lenses due to facies changes within the reservoir rocks. Several accumulations formed in traps associated with the pre-Neogene, tectonically and morphologically developed basement highs, and the pseudoanticlines overlying them. There is example on trap formed in Neogene pseudoanticline overlying magmatic rock masses (for instance at Jászkarajenő). Occasionally traps were also formed in the biogenic limestone bodies developed on the top of former submarine elevations (for instance at Nagykőrös).

The tectonic elements and the sequence boundaries within the Pannonian formations (for instance above and under the Újfalu Sandstone Formation) also play important role in trapping.

Hydrocarbons accumulated in Pannonian sandstones with different facies (turbidite lobe, turbidite channel infill and channel infill on a delta slope) in stratigraphic traps combined with faults, for instance in pseudoanticlines, “roll-over” anticlines, semi-structures leaning against faults (SZENTGYÖRGYINÉ et al. 2012c).

Hydrocarbon occurrences in the northern part of the Nagykunság

Data characterising the discovered reservoirs (hydrocarbon composition, calorific value, etc.) basically are originated from the National Mineral Raw Materials and Geothermal Energy Resources Register of the Mining and Geological Survey of Hungary (MBFSZ), in other cases the source is indicated.

Abony. Carbon dioxide gas field was discovered by the Abony–1 well (1972) of the Hungarian National Oil and Gas Trust (OKGT) in Lower Pannonian sandstone, pre-Pannonian Miocene conglomerate, breccia, limestone and volcanics, as well as Mesozoic limestone reservoir rocks. The five reservoirs are situated in a depth range of 1,811.5 and 2,199.5 metres below sea level (m bsl) (gas-water contact, i.e. GWC) (GAJDOS et al. 1997b, LEMBERKOVICS 2010). The natural gas consists of 94.1% carbon dioxide, therefore its calorific value is merely 1.9 MJ/m^3.

Besenyszög. The Bes–1 well was drilled by the OKGT in 1984 and discovered a high carbon dioxide containing natural gas accumulation in Lower Pannonian formations in a depth of 2,605 m bsl (GWC). The gas contains 79.2% carbon dioxide (CO_2) and 4.5% nitrogen (N_2) with a calorific value of 6.0 MJ/m^3.

Cegléd. The Ce–1 well of the OKGT discovered a small oil accumulation in 1965 in the fractured granite gneiss of the Palaeozoic (Upper Carboniferous) metamorphic basement. The boundary between the oil and the water body underneath (OWC) runs in a depth of 1,389 m bsl. The oil is paraffinic, its density is 930.0 kg/m^3, dissolved gas content 50 m^3/m^3, sulphur content 0.20%. Production of the small scale reservoir was deemed to be uncommercial (GYARMATI et al. 2000, HATALYÁK et al. 2010).

Ebes. This natural gas field was discovered by the Eb–2 well drilled in 1960. The Mesozoic, Eocene and Middle Miocene reservoir rocks consist of eight free gas accumulations.

The natural gas reservoir of the Ebes horizon is in Mesozoic, and Eocene porous limestone and pre-Pannonian Miocene sandstone, situated in a stratigraphic trap in a depth of 1,265 m bsl (GWC). The combustible part of the gas is 63.8%, the calorific value is 24.3 MJ/m^3. The methane content is 60.2%, the amount of hydrocarbon compounds with more than five carbon atoms (C_{5+}) is 2.5 g/m^3, CO_2 9.4%, N_2 9.4%.

The two Lower Pannonian occurrences (Ebes–III and –V horizons) were accumulated in clay-bearing and silty sandstones at a depth of 1,044.5 and 937.5 m bsl (GWC). The combustible part of the natural gas is 71.7 and 91.7%, the calorific value is 27.3 and 34.7 MJ/m^3. The ratio of methane (CH_4) in the gases is 67.6 and 88.0%, CO_2 5.8 and 0.3%, N_2 22.6 and 8.0%, respectively.

The five Upper Pannonian reservoirs can be found in sandstones, and clay-bearing sandstones in a depth of 344.5 and 884.5 m bsl (GWC). The combustible part of the natural gas is 81.0–97.2%, the calorific value is 26.4–36.7 MJ/m^3. The CH_4 is 80.5–96.0%, CO_2 ranges up to maximum 15.2%, N_2 not more than 3.9%.

Ebes North (Ebes-Észak). One of the two free gas accumulations of this natural gas field was discovered by the OKGT with the Eb–1 well in 1960, the other one with the Eb-É–2 well in 1988. These occurrences can be found in Upper Pannonian sandstone in a depth of 466.5 and 835.5 m bsl (GWC). The combustible part in the gases is 81.0 and 97.2% (CH_4 80.5 and 93.8%, C_{5+} in the lower reservoir is 3.7 g/m^3), CO_2 15.6 and 0.4%, N_2 3.4 and 2.4%, respectively. The calorific value of the gases is 29.2 and 34.2 MJ/m^3 (KÁPOSZTA et al. 1972, VARGÁNÉ et al. 1992, SZENTGYÖRGYINÉ et al. 2012a).

Egyek. The Egyek natural gas field was discovered by the OKGT with the Egyek–2 well in 1988, in silty sandstone layers of the Lower Pannonian Szolnok Sandstone Formation, in a depth of 2,072 m bsl (GWC). The calorific value of the gas containing 96.1% combustible substances is 47.6 MJ/m^3. The gas contains 78.1% CH_4, 2.9% CO_2 and nearly 1.0% N_2, 218.5 g/m^3 C_{5+}.

Fegyvernek. The natural gas field consists of 18 reservoirs discovered by the OKGT in 1969 with the Fv–1 well. Reservoirs are in Lower Pannonian silty and marly sandstones in a depth between 1,304.5 and 1,806.0 m bsl (GWC) (Figure 4.5.12). The quality of the gases varies widely, the combustible part is in a range of 14.8–78.9% (CH_4 maximum 75.0%, C_{5+} maximum 28.6 g/m^3), CO_2 3.3–77.6%, N_2 7.2–29.5%. The calorific value of the gases is between 5.8 and 30.4 MJ/m^3. Most of the reserved gases have high inert content; one of them provides 4.94 g/m^3 condensate as well.

Hajdúszoboszló. The natural gas field has the largest initial in-place natural gas resources in Hungary, discovered by the Hsz–2 well in 1958. The hydrocarbons were accumulated mainly in Pannonian and partly in Mesozoic – Palaeogene – Middle Miocene reservoir rocks.

The *Hajdú horizon* consists of one reservoir in Upper Cretaceous – Palaeogene flysch and sandstone–conglomerate succession, and in overlying Sarmatian sedimentary rocks in a depth of 1,212 m bsl (GWC). The combustible part of the gas is 94.0%, the calorific value is 39.7 MJ/m^3, and provides 88 g/m^3 condensate as well. The CH_4 is 77.9%, CO_2 2.1%, N_2 3.8%, C_{5+} 124.2 g/m^3.

The Lower Pannonian occurrences (*Szoboszló–IV. and –V. level*) are in a depth of 990 and 910 m bsl (GWC), their reservoir rock is clay-bearing sandstone. The combustible part of the gases is 94.1 and 96.6%, the calorific value is 35.3 and 33.6 MJ/m^3, CH_4 85.4 and 93.0%, CO_2 0.4 and 0.2%, N_2 7.9 and 3.3%, C_{5+} 22.5 and 15.4 g/m^3. The lower accumulation contains 31 g/m^3 condensate.

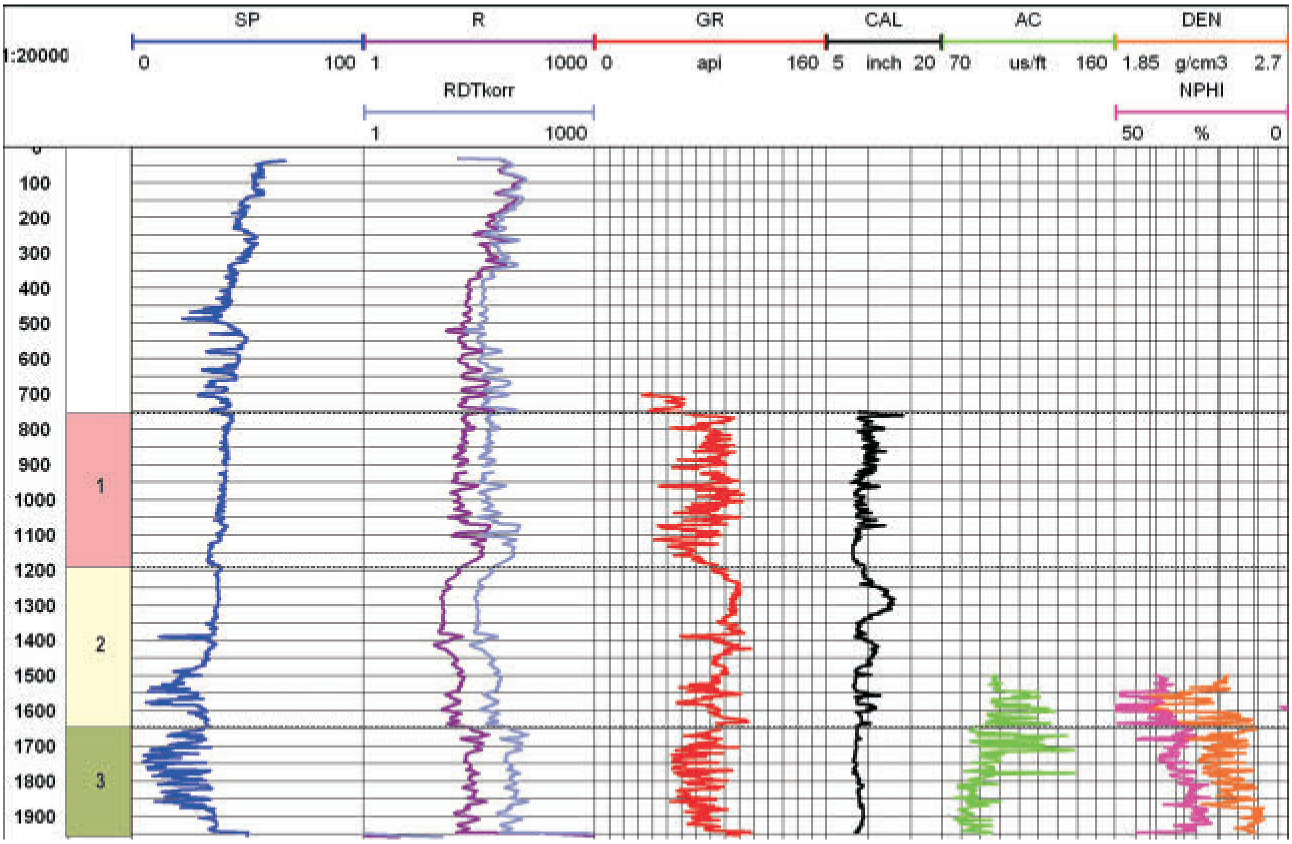


Figure 4.5.12. Characteristic geophysical well logs of the Fegyvernek Fv–18 well

Legend: SP: spontaneous potential, R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log; AC: acoustic profile; DEN: density; NPHI: neutron-porosity log. Geological column: 1. Újfalu Fm (Upper Pannonian), 3. Algyő Fm (Lower Pannonian), 4. Szolnok Fm (Lower Pannonian)

The Upper Pannonian fifteen reservoirs are in a depth between 40 and 836 m bsl (GWC) in clay-bearing sandstone and sandstone, in structural traps with fault closure. The gases have a combustible part of 90.9–97.5%, their calorific value is 34.3–36.2 MJ/m^3, and the proportion of methane may reach as much as 95.6%, that of CO_2 maximum 0.8%, N_2 not more than 8.6%.

Hajdúszoboszló underground gas storage (Hajdúszoboszló gáztároló). It corresponds to Szoboszló–III horizon, found in Lower Pannonian sandstone in a depth of 876 m bsl (GWC). The original combustible part of the gas is 97.0%, the calorific value is 36.4 MJ/m^3 (CH_4 94.2%, CO_2 0.4%, N_2 2.6%).

Jászkarajenő. The occurrence was discovered by the Jászkarajenő Jk–1 well in 1957. The gas accumulated in a trap developed in Neogene pseudoanticline in Lower Pannonian fractured sandy calcareous marl (Endrőd Marl Formation) in a depth of 1,314 m bsl (GWC). The gas contains 79.9% CO_2, the combustible part is merely 12.7%, N_2 is 7.4%, therefore the calorific value is also low 4.9 MJ/m^3 (VÖLGYI et al. 1985, KŐRÖSSY 1992).

Kaba. The natural gas occurrence was discovered by the Kab–2 well in 1957 in a depth of 1,738 m bsl (GWC). The reservoir is in Lower Pannonian sandstone with a structural trap. The calorific value of the gas is 91.8%, the combustible matter is 37.3 MJ/m^3. The gas contains 82.4% CH_4, 3.3% CO_2 and 4.4% N_2 (TATÁRNÉ, PAP 1974).

Kaba North (Kaba-Észak). Three natural gas reservoirs and one oil reservoir with gas cap in Upper Pannonian formations was discovered by the Kab-É–1 well in 1960. The oil reservoir with gas cap is situated in fault closed structural trap in a depth of 970.5 m bsl (OWC) in Upper Pannonian clay-bearing sandstone. The density of the paraffinic type oil is 865.1 kg/m^3, the combustible matter content of the gas in the gas cap is 93.2%, CO_2 content 1.4%, N_2 content 5.3%, the calorific value is 33.5 MJ/m^3 (TATÁRNÉ, PAP 1973).

Natural gases were accumulated in Upper Pannonian clay-bearing sandstone layers in a depth of 982–1024.5 m bsl (GWC), in structural traps. The combustible matter content of the gases are between 93.0 and 94.9%, their calorific value is 33.5 MJ/m^3, CH_4 90.1–94.2%, CO_2 0.6–1.4%, N_2 4.6–6.3% (TATÁRNÉ, PAP 1973).

Karcag. The Karcag undersaturated oil reservoir was discovered by the Kar–1 well in 1989 in the Lower Pannonian Endrőd Marl Formation Tótkomlós Calcareous Marl Member in a depth of 2,366.5 m bsl (OWC). The oil is intermediate with 862.0 kg/m^3 density, and 70.0 m^3/m^3 dissolved gas content. The gas has 86.7% combustible matter content (CH_4 69.1%, C_{5+} 105.4 g/m^3), CO_2 content 8.7%, N_2 ratio 4.6%, the calorific value is 42.4 MJ/m^3.

Karcag–Bucsa. This natural gas field consisting of five reservoirs was discovered by the KB–3 well in 1964, mainly in Lower Pannonian, partly Upper Pannonian and older Miocene formations.

One natural gas reservoir can be found in Middle Miocene Badenian riodacite tuff, tuffite, sandstone and conglomerate reservoir rocks in a depth of 1,757.0 m bsl (GWC). The combustible part of the gas is 91.9%, the calorific value 39.8 MJ/m^3. The methane content is 77.4%, CO_2 2.2%, N_2 5.9%. The gas also provides 186.9 g/m^3 paraffinic condensate as well (Benkő et al. 1996).

Three gas reservoirs are in Lower Pannonian prodelta sandstone (Szolnok Sandstone Fm) in a depth between 1,275.5 and 1,369 m bsl (GWC), in fault closed traps. The combustible matter in the gases is 96.4–97.5% (CH_4 94.4–96.6%, C_{5+} 0.7–3.0 g/m^3), CO_2 content 0.7–1.0%, N_2 content 1.9–2.6%, their calorific value is 35.3–39.8 MJ/m^3.

The Upper Pannonian accumulation is situated in a depth of 897.5 m bsl (GWC) in the sandstone of the Újfalu Formation. The gas has 97.5% combustible matter content (CH_4 96.6%, C_{5+} 2.2 g/m^3), the proportion of CO_2 is 0.7%, that of N_2 is 1.9%, and the calorific value is 35.4 MJ/m^3.

Kenderes South (Kenderes-Dél)**.** This natural gas occurrence was discovered by Toreador Hungary Ltd (later RAG Hungary Ltd) with the THL Ken D–1 exploration well drilled in 2006. It is situated in a depth of 1,424 m bsl (GWC), in the Lower Pannonian Szolnok Sandstone Formation, in a fault closed structural trap. The natural gas has high inert content, the combustible part is merely 19.8% (18.8% CH_4, 8.9 g/m^3 C_{5+}), CO_2 78.2%, N_2 2.0%, therefore the calorific value of the gas is merely 7.6 MJ/m^3, but it also provides 8.9 g/m^3 condensate (Lemberkovics 2009).

Kengyel. The Kengyel carbon dioxide gas accumulation was discovered by the OKGT in 1979 with the Ken–2 well. It can be found in a Middle Miocene (Badenian) sandstone reservoir in a depth of 1,860.5 m bsl (GWC). The combustible part of the natural gas is merely 4.2%, the calorific value is 1.7 MJ/m^3.

Kengyel North–1 (Kengyel-Észak–1)**.** This natural gas field was discovered by the OKGT in 1987 with the Ken-É–1 well. The reservoir rock is sandstone deposited on the boundary of the pre-Pannonian Miocene and the Lower Pannonian succession, in a depth of 1,562 m bsl (GWC) in fault closed structural trap. The calorific value of the gas containing 82.5% combustible matter is 35.9 MJ/m^3. The CH_4 is 73.3%, CO_2 8.2%, N_2 9.3%, C_{5+} 83.9 g/m^3.

The two gas occurrences in Lower Pannonian reservoir rocks were accumulated in a depth of 1,253 and 1,451 m bsl (GWC) in sandstone (partly in the Szolnok Sandstone Formation). The combustible part of the gases is 91.6%, CH_4 90.9%, CO_2 1.0%, N_2 7.4%, C_{5+} 2.9 g/m^3. The calorific value of the gases is 33.2 MJ/m^3.

Kisújszállás North-east (Kisújszállás-Északkelet). It was discovered by Mol Hungarian Oil and Gas Plc with the Kis-ÉK–4 well in 1995 in a depth of 1,179 m bsl (GWC). The natural gas was accumulated in Lower Pannonian sandstone reservoir rocks. The gas has a combustible matter content of 95.6% (CH_4 94.3%, C_{5+} 1.9 g/m^3), CO_2 content 0.5%, the proportion of N_2 is 3.9%, the calorific value is 34.7 MJ/m^3.

Kisújszállás East (Kisújszállás-Kelet). This natural gas field was discovered in 1958 with the Kis–2 well. The gas is accumulated in Middle Miocene and Lower Pannonian formations.

The gas of the Middle Miocene accumulation was trapped in limestone with lithological closure in a depth of 1,430 m bsl (GWC). The calorific value of the gas containing 94.8% combustible matter is 37.8 MJ/m^3. Methane content is 84.3%, CO_2 0.2%, N_2 5.0%.

The three Lower Pannonian occurrences are stored in sandstone in a depth between 1,165.5 and 1,303 m bsl (GWC), in fault closed traps. The combustible part is 91.6–92.6%, the calorific value 39.5–39.7 MJ/m^3. The CH_4 content of the gas is 82.7–88.1%, CO_2 0.3–0.6%, N_2 is 6.9–8.1%.

Kisújszállás West (Kisújszállás-Nyugat). This natural gas field was discovered by the Kis–12 well in 1969. Most of its reservoirs can be found in Lower Pannonian sedimentary rocks, two of them are in Middle Miocene formations.

The pre-Pannonian Middle Miocene occurrences have been accumulated in volcanics and tuffaceous sandstone reservoirs in a depth of 1,747 and 1,547.5 m bsl (GWC). The combustible part of their gases is 60.6 and 57.3%, CH_4 56.0 and 37.8%, CO_2 13.7 and 33.6%, N_2 25.7 and 23.7%, C_{5+} 11.9 and 13.2 g/m^3, the calorific value is 23.7 and 17.5 MJ/m^3 respectively. The reservoir of the lower, tuffaceous sandstone is of somewhat better quality than the upper reservoir.

The seventeen Lower Pannonian reservoirs were accumulated in silty sandstone succession in a depth of 1,165–1,563.5 m bsl (GWC). The combustible part of the natural gases varies between 46.3 and 83.2%, the calorific value is 17.0–31.3 MJ/m^3. The respective volumes in the gases are 43.1–80.0% for CH_4, 0.3–46.9% for CO_2, and 6.8–41.1% for N_2. The amount of C_{5+} is mostly in the 2.5–28.4 g/m^3 range.

Nádudvar South-west (Nádudvar-Délnyugat). This hydrocarbon field, accumulated in Lower Pannonian and older Miocene rocks, consisting of one oil accumulation with gas cap and six natural gas accumulations, was discovered by the Nu–1 well in 1953 (Bujdosó et al. 1997).

The oil with gas cap is situated in a depth of 1,545 m bsl (OWC) in Middle Miocene marl, calcareous marl, and sandy marl with lithologic closure. The density of the paraffinic–intermediate type oil is 948.0 kg/m^3, the dissolved gas content 150 m^3/m^3. The combustible part of the dissolved gas is 95.8%, the calorific value is 36.7 MJ/m^3.

The Middle Miocene natural gas occurrence is situated in a depth of 1,530 m bsl (GWC) in tuffaceous siltstone and volcanic agglomerate reservoir rocks in lithologic trap. The combustible part of the gas is 91.1% the calorific value is 36.8 MJ/m^3.

Natural gases of five reservoirs were accumulated in a depth of 1,441–1,590 m bsl (GWC) in Lower Pannonian calcareous marl, clay-bearing sandstone, and sandy marl, in lithologic traps. Gases contain 85.5– 97.8 combustible matter; the CH_4 is 85.5–92.5%, with maximum 1.9% CO_2, and 7.5–13.6% N_2, the calorific value is 34.0–37.7 MJ/m^3.

Nádudvar North-east (Nádudvar-Északkelet). It was discovered by the Nu–3 exploratory well in 1953. The field consists of two undersaturated oil and four natural gas occurrences in Pannonian formations.

The two undersaturated oil reservoirs can be found in a depth of 1,581.5 and 1,310 m bsl (OWC) in Lower Pannonian sedimentary rocks. The oil in the lower calcareous marl reservoir is of intermediate type, with 859.0 kg/m^3 density. The oil of the upper reservoir trapped in the clay-bearing sandstone is paraffinic, with a density of 856.0 kg/m^3. Dissolved gas content is 50 m^3/m^3 in both accumulations with combustible matter content of 96.9 and 91.9%, calorific value of 34.7 and 37.5 MJ/m^3, respectively. The CH_4 ratio is 99.8 and 84.5%, that of CO_2 is 0.5 and 6.8%, that of N_2 is 2.7 and 1.4%, respectively.

The Lower Pannonian natural gas occurrence is in a depth of 1,436 m bsl (GWC), accumulated in clay-bearing sandstone and sandstone, in a trap with lithological closure. The combustible part in the gas is 93.4% (CH_4 87.7%), CO_2 1.7%, N_2 2.9%. The calorific value of the gas is 37.0 MJ/m^3.

The three natural gas accumulations trapped in Upper Pannonian sandstone and clay-bearing sandstone lie in a depth of 1,015–1,100 m bsl (GWC). The combustible matter content in the gases is 99.8%, which is exclusively methane; the calorific value is 35.8 MJ/m^3.

Nagykőrös. The Nk–2 well discovered it in 1957. The field has two oil accumulations with gas cap and five carbon dioxide occurrences in Permian, Jurassic, Middle Miocene and Lower Pannonian formations, associated with an approximately 10 km long basement elevation structure running between the cities of Nagykőrös and Kecskemét in north–north-east – south–south-west direction. The Nagykőrös Nk-Ú–3 and –6 wells drilled in 1980–81 were also productive for CO_2 gas.

The Permian carbon dioxide natural gas occurrence of the basement (NK–2) was accumulated in sandstone succession at a depth of 987 m bsl (GWC). The carbon dioxide content of the gas is 96.1%, N_2 2.7%, combustible matter merely 1.1% (calorific value 0.4 MJ/m^3).

The Lower Jurassic (Liassic) oil accumulation with gas cap (Nagykőrös–Kálmánhegy, NKK) is situated in the basement at a depth of 1,063 m bsl (OWC) in limestone–sandstone succession in traps developed by stratigraphic changes. The oil is paraffinic type with 892.3 kg/m^3 density. The dissolved gas (90 m^3/m^3) consists of 34.4% combustible matter (33% CH_4), 54.7% CO_2 and 10.9% N_2, the calorific value is 13 MJ/m^3.

The Middle Miocene oil accumulation with carbon dioxide gas cap (Nagykőrös–1, NK–1) sits in a depth of 1,028 m bsl (OWC). The reservoir, closed by lithological and facies change, is mainly Badenian sandstone and conglomerate, and to a smaller extent Sarmatian fractured marl. The oil is paraffinic with 873 kg/m^3 density. The dissolved gas content is 115 m^3/m^3, and the gas consists of 97.0% of carbon dioxide, with very low combustible gas ratio (1.3%) and N_2 (1.7%) (GYARMATI et al. 2000, 1982; VÖLGYI et al. 1985).

The Lower Pannonian natural gas occurrences were accumulated in sandstone reservoirs in a depth of 863–930 m bsl (GWC). The gases consist of 83.1–88.5% CO_2, 4.5–7.7% N_2, and merely 7.0–9.3% combustible matter.

Nagykőrös South (Nagykörös-Dél)**.** Mol Hungarian Oil and Gas Plc discovered this field in 2007 with the Nk-D–2 well. It has six natural gas accumulations in a depth range of 601 and 727 m. The reservoir rocks are made up of Upper Pannonian sedimentary rocks with alternating clay and sandstone layers. The calorific value of the gases is 3.9–19.8 MJ/m^3. The two upper occurrences (NkD2Pl2–1 and NkD2Pl2–2) provide combustible gas, the gases in the other accumulations are not combustible, or not known due to lack of explorations (HATALYÁK et al. 2010).

Nagykőrös South – Kecskemét (Nagykörös-Dél–Kecskemét). This natural gas field was discovered by the Nk-D–1 well in 1959. It consists of four reservoirs in pre-Pannonian Miocene and Lower Pannonian rocks.

The pre-Pannonian Miocene accumulations sit in conglomerate, sandstone, and silty sandstone in a depth of 981 and 951 m bsl (GWC). The combustible part of the natural gases is 52.1 and 52.6%, CH_4 51.2%, CO_2 25.8%, N_2 22.0%, C_{5+} 1.6 g/m^3. The calorific value of the gases is 18.1 and 21.0 MJ/m^3.

The gas occurrences in Lower Pannonian sandstones and clay-bearing sandstones are in a depth of 835 and 794.6 m bsl (GWC). The combustible part is 54.0 and 41.9%, CO_2 43.8 and 39.7%, their calorific value is 19.3 and 14.5 MJ/m^3, respectively. In the gas of the upper reservoir the CH_4 is 41.2%, N_2 is 18.5%, C_{5+} quantity is 1.1 g/m^3.

Nagykörű. The gas field was discovered by the OKGT in 1964. Natural gases were accumulated in 21 Pannonian silty sandstone reservoirs. The occurrences are situated in a depth between 1,530 and 1,875.5 m bsl (GWC). The field includes combustible, as well as high inert containing gases, and carbon dioxide accumulations as well. The combustible part of the gases varied widely, ranging from a few per cent up to 95.9%, their calorific value is 0.8–29.1 MJ/m^3. The gas contains 2.2–95.9% CH_4, 1.9–93.9% CO_2, 3.8–42.9% N_2, the C_{5+} max. 13.3 g/m^3.

Nagykörű West (Nagykörű-Nyugat). This natural gas field was discovered by the OKGT with the Nkö–1 well in 1964 in Lower Pannonian silty sandstone at a depth of 1,686.5–1,866.5 m bsl (GWC). The eight natural gas occurrences include two CO_2 accumulations beside the combustible gas accumulations. The combustible part in the gases varies between 3.2

and 69.6%, their calorific value is from 14.0 to 25.5 MJ/m^3. The CH_4 ratio is 2.7–68.1%, the C_{5+} is not more than 41.5 g/m^3, CO_2 4.7–93.1%, N_2 3.7–42.2%.

Örményes South-east (Örményes-Délkelet). POGO Magyarország Kft. (POGO Hungary Ltd) discovered a carbon dioxide reservoir in 2003 by the Pogo Örm DK–1 well in the Lower Pannonian Szolnok Sandstone Formation at a depth of 1,707 m bsl (GWC). The gas contains merely 3.7% combustible part, it has a calorific value of 1.5 MJ/m^3 and beside 94.4% CO_2 3.4% CH_4 and 1.9% N_2, as well as 1.0 g/m^3 condensate (LEMBERKOVICS 2009).

The natural gas reservoir which belongs to this field is in 1,594 m bsl (GWC). The gas contains 72.8% combustible part, and the calorific value is 29.6 MJ/m^3. Methane content is 68.3%, CO_2 24.6%, N_2 1.8%. The gas provides 5.0 g/m^3 condensate.

Örményes East (Örményes-Kelet). The natural gas field was discovered by Pogo Hungary Kft. with the Pogo Örm K–3 well in 2004 in a depth of 2,070–2,168 m bsl (GWC) in Middle Miocene formations, partly in Badenian sandstone, tuffaceous sandstone (Abony Formation), and in sandstone intercalated with claystone and siltstone. The natural gases accumulated in structural traps contain 44.2–93.9% combustible gases, the CH_4 is 42.6–84.2%, CO_2 2.6–34.0%, N_2 3.2–21.9%, the C_{5+} is 3.4 g/m^3. The calorific value of the gases is 15.7–36.9 MJ/m^3, the condensate content in two accumulations is 3.35 g/m^3 (BATES 2004, LEMBERKOVICS 2009).

Penészlek. After the early exploration realised in the 1980s, several natural gas reservoirs were discovered by the wells drilled on the base of the seismic measurements of Geomega Ltd and PetroHungaria Ltd in 2010: Penészlek–P104, Penészlek-Észak–P/2, Közép-Penészlek-MA, Fülöp-K-MA Pen–101 and Fülöp-Ny-MA Pen–105. These natural gas reservoirs were located between a depth of 935 and 1,280 m bsl (GWC) in Lower Pannonian prodelta sandstone (Algyő Formation) and in Middle Miocene tuff, zeolitised tuff, calcareous tuffite (Tokaj Volcanic Group and Ebes Formation) reservoir rocks (WÓRUM et al. 2010).

The Penészlek–P104 accumulation, the bulk of which has been produced, is divided into two structural blocks of roughly the same size by an oblique fault of northern–southern strike. The combustible part of the natural gas is 97%, the calorific value is 34.2 MJ/m^3. The gas also provides condensate with 761 kg/m^3 density and 44.7 MJ/m^3 calorific value.

Several gas saturated layers were identified in the multiple reservoirs of the Fülöp reservoir group, which has statigraphic closure. The gas saturated layers are separated from each other by impermeable, low gas saturation level tuff layers, which however are slightly fractured and therefore all of the gas saturated layers have the same gas-water contact. The combustible part of the gases is 98.5 and 99.1%, the calorific value 36.7 and 36.6 MJ/m^3. The CH_4 is 91.6 and 92.3%, CO_2 0.02 and 0.01%, N_2 1.4 and 0.9%, C_{5+} 20.3 and 11.7 g/m^3. A natural gas accumulation (Fülöp–IMP) formed in the "impermeable Miocene" succession was also found in the Fülöp gas field which can be produced only using so unconventional techniques as fracturing (WÓRUM et al. 2010).

Based on the reassessment of PetroHungaria Ltd three additional gas reservoirs can be identified in the Penészlek North field: Pen-É–P/1 and Pen-É–P/2 are Lower Pannonian reservoirs, and PenÉszak-MA is a Miocene reservoir. The two Lower Pannonian gas saturated fine-grained sandstone layers deposited in prodelta environment, can be classified into the Algyő Formation. Reservoirs are fault bordered structural traps in a depth of 1,115 and 1,132 m bsl (GWC). The calorific value of the natural gases containing 97–98% combustible part is 37.0 and 43.1 MJ/m^3, respectively.

Reservoirs known as Közép Penészlek (Közép-Penészlek-MA) and Penészlek West (Penészlek-Nyugat-MA) are located in a depth of 1,175 and 1,138 m bsl (GWC) in fault-delineated structural traps in Miocene calcareous tuffite and sandy–calcareous tuff layers classified as Tokaj Volcanic Group and Ebes Formation. The combustible part of the natural gas is 99%, the calorific value is 41.0 MJ/m^3.

Penészlek (along the national border) (Penészlek határmenti). After the success of the hydrocarbon exploration in neighbouring Romania, the OKGT drilled the first exploration well (Pen–1) in the Penészlek area in 1982. The well drilled a natural gas accumulation in tuff, tuffite, and tuff-laminated calcareous sandstone succession situated in the top zone of the volcanoclastic Middle Miocene (Badenian–Sarmatian) succession. Further research discovered that the gas field consists of several hydrodynamically isolated sections. A part of an elevated basement structure (Penészlek East) identified at the Hungarian–Romanian border runs in the area, with the greater part assumed to be in Romanian territory. The smaller part of another closing structure (Penészlek West) falls into the Romanian side of the national border. The three natural gas occurrences are located in a depth of 1,125–1,173.5 m bsl (GWC), the combustible part of the gas is 96.1–99.7%, and the calorific value is 39.7–41.0 MJ/m^3. Gases contain 87.3–91.1% CH_4, CO_2 0.1–2.1%, N_2 0.2–1.9%, C_{5+} 59.5–63.9 g/m^3 (VÖLGYI et al. 1983, 1985a, b; WÓRUM et al. 2010). The seismic measurements explored several structural basement high elevations in this region. However, production in the borderland accumulations was abandoned.

Püspökladány. This field discovered by the Pü–2 well drilled in 1955 consists of one oil reservoir with gas cap and one natural gas reservoir. Reservoir rocks are Palaeogene and Middle Miocene formations.

The oil reservoir is in flysch, and flysch-like sedimentary rocks in a depth of 1,854.5 m bsl (OWC). The density of the paraffinic oil is 848 kg/m^3. The combustible part of the gas is 86.5% with a 35.2 MJ/m^3 calorific value. It contains 78.5% CH_4, 10.1% CO_2 and 3.4% N_2, the C_{5+} content is 329.1 g/m^3.

The natural gas reservoir is in pre-Pannonian Miocene calcareous sandstone, marl, and silt at a depth of 1,861 m bsl

(GWC). The gas consists mainly of carbon dioxide, the combustible part in it is 15.8%, the methane content is 13.8%, N_2 3.3%, the calorific value of the gas is 7.8 MJ/m^3, and the condensate content is 137.4 g/m^3.

Rákóczifalva. The field discovered in 1954 by the Rá–1 well consists of two natural gas reservoirs. The accumulated gas is built up mainly of CO_2, located in Lower Pannonian formations in a depth of 1,348 and 1,287 m bsl (GWC). The lower reservoir is in clastic, silt containing formation with mixed lithological composition and the upper reservoir is in silty sandstone. Gases consist mainly of CO_2, the combustible part is merely 21.3 and 7.0%, the C_{5+} 30.5 g/m^3, the N_2 is 2.9 and 2.0%, respectively.

Szandaszőlős. The Szandaszőlős natural gas field was discovered in 1958 by the Sza–1 well. Four reservoirs can be found here in Lower and Upper Pannonian sandstones, and silty sandstone reservoirs (Szolnok and Újfalu Sandstone Formations) in a depth of 875–1,606 m bsl (GWC). The combustible part of the gases is 78.8–81.5%, the calorific value 28.9–31.4 MJ/m^3, CH_4 76.0–78.8%, the CO_2 maximum is 3.1%, the N_2 is 17.6–20.3%. The re-evaluation of earlier data (LEMBERKOVICS 2010) suggests that sufficient remaining natural gas resources can be found in the field which could be commercially exploited using tertiary production technologies. A part of these resources could be successfully delineated, the other part however was not possible because of the complicated structural–stratigraphic traps and the lack of local data.

Szolnok. The Szo–1 well discovered an undersaturated oil accumulation in Lower Pannonian sandstone at a depth of 1,827 m bsl (OWC) in 1953. It has paraffinic oil with 876.0 kg/m^3 density, and contains 60 m^3/m^3 dissolved gas and 0.4% sulphur. The combustible matter content of the dissolved gas is 72.0%, and contains 13% CO_2 and 15% N_2, the calorific value is 33.0 MJ/m^3.

Szolnok South-west (Szolnok-Délnyugat). This natural gas accumulation found in silty sandstone of the Lower Pannonian Szolnok Sandstone Formation in a depth of 1,672 m bsl (GWC) was discovered by the Szo-DNy–1 well completed in 1990. It is found in a fault closed structural trap. The combustible part of the gas is 90.1%, the calorific value is 36.5 MJ/m^3. The methane is 82.0%, CO_2 2.7%, N_2 7.3%, the amount of C_{5+} is 31.6 g/m^3.

Szolnok–Hajtótanya. This natural gas accumulated in Lower Pannonian silty sandstone reservoir (Szolnok Sandstone Formation), in structural trap was discovered in 1956 by the SzH–13 well in a depth of 1,660 m bsl (GWC). The gas contains 83.5% combustible part, the calorific value is 35.1 MJ/m^3, N_2 14.8%, CO_2 is 1.5%, and the C_{5+} is 17.2 g/m^3.

Szolnok–III. The field discovered by the Szo-É–2 well in 1991 consists of one undersaturated oil reservoir and three natural gas reservoirs, which are located in Lower Pannonian prodelta and transgressional sandstone in a depth of 1,700–1,802.5 m bsl (GWC, and OWC), in fault closed structural traps.

The oil is paraffinic type with 914.0 kg/m^3 density, it contains 30 m^3/m^3 dissolved gas, the calorific value of which is 36.7 MJ/m^3.

The natural gas occurrences consist mainly of CO_2, their calorific value is about 1.3 MJ/m^3.

Tatárülés–Kunmadaras. The Km–1 well discovered this field of three natural gas reservoirs in 1956. Gases were accumulated in Lower Pannonian clay-bearing and silty sandstones in a depth of 1,040–1,152.5 m bsl (GWC) in lithologically closed stratigraphic traps. The calorific value of the gases containing 97.1–97.9% combustible part is 35.4–36.6 MJ/m^3. They consist of 96.5–97% CH_4, the CO_2 is maximum 0.5%, N_2 1.6–2.5% and the C_{5+} is 3.0–9.0 g/m^3.

Tiszagyenda. The OKGT discovered a high inert containing natural gas reservoir in 1987 with the Tigy–3 well in pre-Pannonian Miocene tuffaceous sandstone and tuff at a depth of 2,575 m bsl (GWC), in structural trap formed in the top zone of the Middle Miocene. The calorific value of the gas is 14.4 MJ/m^3 because of the 39.9% combustible part, consisting mainly of CH_4 (39.5%), 35.4% CO_2, 24.8% N_2, and some sulphur dioxide. The gas contains 61.6 g/m^3 intermediate type condensate (ERDEI et al. 1997a).

Tiszakécske. It was discovered by the THL-Tik–1 well in 2008 in Lower Pannonian turbidite sandstone (Szolnok Sandstone Formation), at a depth of 1,900 m bsl (GWC), in a tectonically closed stratigraphic trap. The natural gas is set up mainly of CO_2 (89.6%), with some N_2 (6.6%) and combustible part (3.9%), therefore the calorific value is merely 1.5 MJ/m^3, and it also provides 1.8 g/m^3 condensate.

Tiszapüspöki. Reservoirs of this natural gas field discovered by the Tip–1 well in 1964 can be found in Lower Pannonian silty sandstone in a depth of 1,519.5 m bsl (GWC). The calorific value of the gas containing 64.4% combustible matter is 23.9 MJ/m^3. The CH_4 ratio is 62.6%, CO_2 12.6%, N_2 23.0%, C_{5+} 2.4 g/m^3.

Tiszaszentimre. It was discovered by the Mol Hungarian Oil and Gas Plc with the Tiszi–2 well drilled in 2012. The two natural gas occurrences were formed in the sandy turbidite succession of the Lower Pannonian Szolnok Sandstone Formation. They can be found in a depth of 1,206–1,217 m bsl (GWC), with 99.3% combustible matter content, their calorific value is 33.9 MJ/m^3. The methane content is 99.1%, the CO_2 and N_2 are 0.3–0.4%, the C_{5+} is 0.2 and 0.4 g/m^3 (SZENTGYÖRGYINÉ et al. 2012c).

Tószeg. It was discovered by the Tósz–3 well in 1990. The field consists of three high inert containing natural gas accumulations in structural traps of the Lower Pannonian Szolnok Sandstone Formation at a depth of 1,405–1,582.9 m bsl (GWC). The CO_2 content of the gases varies between 53.5 and 70.2%, they contain 27.4–43.2% combustible matter (25.4–40.6% CH_4), and 2.3–2.4% N_2, their calorific value is 11.9–24.0 MJ/m^3. The middle accumulation is of poorer quality than the other two.

Törökszentmiklós. The Tör–1 well completed in 1986 discovered this field. Four natural gas occurrences were formed here in Lower Pannonian silty sandstone in a depth of 1,476–1,759 m bsl (GWC). The upper reservoir (VIII-Pl1–7) is of the best quality, containing 94.7% combustible part, the calorific value is 34.6 MJ/m^3. The CH_4 is 93.0%, CO_2 1.3%, N_2 4.0%, the C_{5+} is 1 g/m^3. In the reservoir below it (VIII/PL1–11/1/2) there is much CO_2 (57.6%) and N_2 (11.0%), the combustible part is 31.3% (30.1% CH_4, 12.7 g/m^3 C_{5+}). The calorific value of the gas is 12.1 MJ/m^3. The two lower accumulations consist of 86.0% CO_2, supplemented with 5.8% N_2 and merely 8.3% combustible part (methane 8.3%, C_{5+} 1.9 g/m^3, the calorific value is 3.1 MJ/m^3).

Törökszentmiklós South (Törökszentmiklós-Dél)**.** The natural gas field has two reservoirs locating in Lower Pannonian sandstone and marly sandstone in a depth of 1,753–1,811 m bsl (GWC) and was discovered by the Tör-D–1 well in 1986. The gases have high inert content, CO_2 portion is 56.6 and 54.8%, combustible part 35.2 and 40.7% (methane content is 32.1 and 37.2%, the quantity of C_{5+} 21.8 and 19.7 g/m^3), N_2 8.2 and 4.5%, their calorific value is merely 14.6 and 15.8 MJ/m^3, respectively. The lower reservoir provides 34.1 g/m^3 condensate as well.

Törtel. The field discovered in 1956 by the Tö–4 well consists of two undersaturated oil reservoir and one high inert containing natural gas reservoir, accumulated in Pannonian formations in lithologically closed traps in Neogene pseudoanticline overlying the structurally and stratigraphically formed basement elevation structure.

Oil accumulations are in Upper Pannonian sandstone in a depth of 902.7 and 900 m bsl (OWC). The oil is intermediate with 920.0 and 900.0 kg/m^3 density, containing 0.8–3.3% sulphur and 40–55 m^3/m^3 dissolved gas. The combustible part of the gas is 8.2% (in the lower oil accumulation) and 39.4% (in the upper oil accumulation), CO_2 content 89.2 and 55.0%, N_2 5.6 and 2.6%, respectively. The calorific value of the dissolved gases is 2.9 and 15.5 MJ/m^3, respectively.

The natural gas was accumulated in Lower Pannonian sandstone in a depth of 1,420 m bsl (GWC). The combustible part of the gas is 27.1%, the CH_4 27.0%, CO_2 67.2%, N_2 5.7% (VÖLGYI et al. 1985).

Turgony. A small sized natural gas reservoir was discovered by the Tg–1 well in 1964 in Upper Pannonian sandstone in a depth of 667 m bsl (GWC). The combustible part of the gas is 96.1%, the calorific value is 35.4 MJ/m^3, CH_4 92.7%, CO_2 2.4%, N_2 1.5%.

Túrkeve North-west (Túrkeve-Északnyugat). Three natural gas reservoirs were discovered by the wells HHE-Túrkeve-Nyugat–5, –7, and –13 in 2009. The Hidden reservoir drilled by the HHE-Túrkeve-Nyugat–5 well and the Hidden West reservoir explored by the Túrkeve-Nyugat–13 well are located in the upper part of the Lower Pannonian Szolnok Sandstone Formation, in clay-bearing silty sandstone. The North Suicide reservoir found in the top zone of a structural elevation discovered by the Túrkeve-Nyugat–7 well is situated in the lowest sandstones of the Szolnok Sandstone Formation. Two of the three natural gas accumulations are of a better quality, the combustible part of the gases is 98.4–98.7%, the calorific value is 33.6– 33.7 MJ/m^3, the CH_4 is 98.1–98.4%, CO_2 0.7–1.0% and N_2 0.6%. The third, North Suicide gas accumulation has a combustible part of 68.0% with 61.3% methane, 30.6% CO_2 and 1.4% N_2. The calorific value of the gas is 26.6 MJ/m^3.

Túrkeve West (Túrkeve-Nyugat). This natural gas field was discovered by the Te–11 well in 1963. Reservoirs are situated in the Variscan basement metamorphic rocks and in Lower Pannonian formations in combined structural and stratigraphic traps.

The reservoir of the metamorphic basement can be found at a depth of 1,996.5 m bsl (GWC) in a fractured, brecciated, cataclastic gneiss rock. The combustible part of the gas is 94.2%, the CH_4 is 84.6%, CO_2 2.7% N_2 3.1%, the C_{5+} is 56.5 g/m^3. The calorific value of the gas is 39.5 MJ/m^3.

The Lower Pannonian occurrences which are in a depth of 1,718–1,775 m bsl (GWC), accumulated in a multiple divided prodelta sandstone thickening towards the west. The combustible part of the natural gas in the lower reservoir is 90.4%, the calorific value 40.0 MJ/m^3, CH_4 81.0%, CO_2 2.9%, N_2 6.7%, the C_{5+} is 128.0 g/m^3. The gases of the two upper reservoirs consist however mainly of CO_2 (72.1–87.9%), the combustible part of them is 24.7 and 10.6%, CH_4 23.6 and 10.3%, N_2 3.6 and 1.5%, the C_{5+} is 3.2 and 1.4 g/m^3. The calorific value is 9.0 and 4.0 MJ/m^3 (SZENTGYÖRGYINÉ et al. 1993).

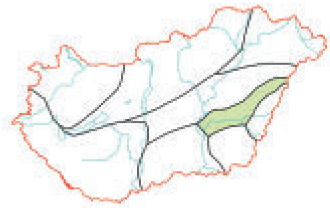
Újszilvás. A CO_2 reservoir was discovered in 1976 by the Újszil–3 well in a depth of 2,004.4 m bsl (GWC) in the top zone of Variscan metamorphic rocks (mica schist, gneiss, migmatite) constituting the crystalline basement complex. The boundary of the reservoir is uncertain both in horizontal and vertical directions. The gas accumulated in a stratigraphic trap. The natural gas has hardly any combustible matter, the CH_4 contain is 1.3%, the calorific value is 0.6 MJ/m^3 (KOMJÁTI et al. 1979, VÖLGYI et al. 1985).

Zagyvarékas. Carbon dioxide gas reservoir was discovered by the Za–1 well in 1960 in Lower Pannonian sandstone in a depth of 1,957 m bsl (GWC). The calorific value of the gas is 1.5 MJ/m^3, the methane content is merely 3.5% in it.

Zagyvarékas North (Zagyvarékas-Észak). This natural gas accumulation was discovered by the Za-É–1 well in 1962 in a depth of 1,323 m bsl (GWC) in Lower Pannonian sandstone, in a trap with tectonic closure. The combustible part of the gas is 25.4, the calorific value is 9.5 MJ/m^3, CH_4 21.5%, CO_2 67.2%, N_2 7.4%, the C_{5+} is 6.6 g/m^3.

All in all the overwhelming majority (94%) of the hydrocarbon reservoirs discovered so far in the northern part of the Nagykunság area with flysch basement is natural gas, the rest are undersaturated oil and oil accumulations with gas cap. Therefore, by further exploration of this area, new hydrocarbon fields, mainly natural gas fields, are expected to be discovered.

Hydrocarbon exploration areas in Hungary — The southern part of the Nagykunság area



4.6

Edit Thamó-Bozsó

Exploration history

In the middle part of the Tiszántúl (eastern–south-eastern part of Hungary) oil and natural gas exploration started in 1941–42, as the company Seismos carried out gravity measurements for the Hungarian–German Mineral Oil Works Co (MANÁT, Kőrössy 2005b). The research identified a structure, in the top zone of it Biharnagybajom Bi–1 well was drilled in 1946 and discovered an oil accumulation with gas cap, which was in production up to 1964. In the 1950–60s the Eötvös Loránd Geophysical Institute of Hungary (MÁELGI) carried out here gravity and magnetic surveys of country-wide scale. As a result of these positive gravity indications were found for instance in the Gyoma–Dévaványa line, to the east of Túrkeve, in the Köröstarcsa, Körösladány and Szeghalom–Füzesgyarmat areas, a smaller magnetic anomaly between Köröstarcsa and Körösladány, and a gravity anomaly series with an axis of SW–NE direction in the Szarvas, Endrőd and Endrőd North areas. In 1954 seismic research started as well. From 1960 the Hungarian National Oil and Gas Trust (OKGT) explored the area and hydrocarbon exploration wells were drilled on the basis of positive seismic indications. As a result of the drillings, hydrocarbon occurrences were discovered at the area of Endrőd and Szarvas in 1961 and at Túrkeve in 1962, respectively.

From the 1970s the seismic, gravity, magnetic and geoelectrical measurements resulted in setting hydrocarbon exploration wells which led to the discovery of a number of fields around Endrőd, Füzesgyarmat, Köröstarcsa, Kaba and Kunszentmárton. Later in the 1980s further fields were identified at Dévaványa, Szeghalom, Martfű, Mezőtúr, Földes, Körösladány and Sáránd. In the period between 1985 and 1989 the Cracow Geophysical Company also carried out geoelectrical measurements. In the Dévaványa South area an OKGT–USGS (Hungarian National Oil and Gas Trust – United States Geological Survey) cooperation project detected "onlap" pinching out of the basal turbidites of the Lower Pannonian on the limbs of the basement rocks structure. Déva-D–1 well at Dévaványa was drilled in 1988 with funding from the World Bank, where measurements were also made by the Canadian Teknica company. The Déva-D–2 well drilled in 1989 managed to discover oil reservoir.

From 1992 3D seismic measurements were also applied, and mainly Mol Hungarian Oil and Gas Plc carried out hydrocarbon explorations here (for instance Boncz et al. 1994; Pap, Nagy 1997a, b; Gajdos et al. 1997b). New reservoirs were discovered in the Monostorpályi South-east, Hosszúpályi South, Földes North-east and Hajdúbagos East areas, and with the wells marked Beru (Berettyóújfalu) unconventional natural gas reservoirs (tight gas sandstone) were also identified.

From the end of the 1990s Hungarian Horizon Energy Ltd carried out explorations in the Túrkeve–Vésztő, and the Túrkeve–Vésztő–Elek–Lökösháza areas among others using 2D and 3D seismic measurements to identify hidden or unconventional hydrocarbon reservoirs. As a result, further natural gas deposits were discovered in the neighbourhood of Dévaványa, Túrkeve and Endrőd (Járai et al. 2010; Szabó et al. 2011, 2013b).

In the Tisza exploration area, which slightly overlaps the southern part of the Nagykunság, in the beginning of the 2000s Gustavson Associates Inc conducted research to discover conventional occurrences and unconventional, basin centred gas accumulations (BCGA).

RAG Hungary Central Ltd conducted explorations in the Szolnok, Kőrös, and Endrőd–III/C areas. Natural gas reservoirs were discovered in the latter area, and the RAG-Öcs–1 well drilled at Öcsöd also proved to be productive.

The southern part of the Nagykunság area holds nearly 250 hydrocarbon reservoirs of 36 fields.

Geological overview

The area is situated to the south of the Mid-Hungarian Fault Zone, on the Tisza Mega-unit originating from the European plate. Within this, it is found mainly on the area of the Villány–Bihor Unit, and to a smaller extent on the Mecsek–Szolnok Unit (Figure 2.3). The terranes and sub-terranes belonging to the Tisza Mega-unit were united during the Variscan orogenic phase (Császár 2005). Barrow-type, amphibolite facies metamorphism took place as an impact of the Variscan deformation some 330–350 million years ago (Árkai et al. 1985, Szederkényi 1998), and then 270–330 million years ago low pressure Variscan heating led to the formation of granite.

In the beginning of the Late Cretaceous the Variscan metamorphic rocks of the Villány–Bihor Unit as a nappe folded from the south, south-west onto the Mesozoic formations of the Mecsek–Szolnok Unit as a result of strong compression.

The Mesozoic low grade metamorphic rocks of the Mecsek Unit popped up as windows from below the nappe in the Bagamér and Endrőd areas. The nappe structure with SW–NE direction of the Tisza Mega-unit was formed as a result of the compression, and shortening structural transformation (Figure 4.5.1).

Basement formations

The major part of the pre-Cenozoic basement in the area is set up by Variscan metamorphic rocks, primarily gneiss, mica schist and amphibolite (Figure 4.5.1, 4.6.1). They were explored by several wells from the 1960s, and in many cases they were considered to be Proterozoic rocks. Later however as the so-called "crystalline basement" was better known, it turned out that these rocks are younger, typically Variscan (SZEDERKÉNYI 1998). Such rocks were mostly reached in a depth below

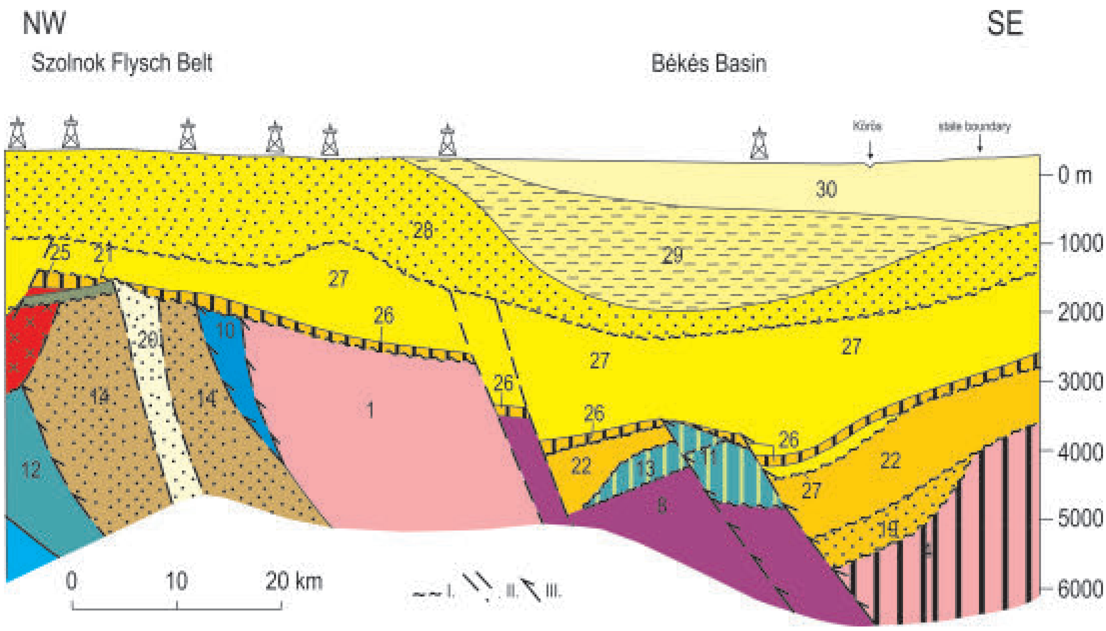


Figure 4.6.1. North-west-south-east direction section crossing the western part of the area and its wider environment adapted from SZEDERKÉNYI et al. (in HAAS ed. 2012, p. 146)

Legend: 1 and 4. Variscan metamorphic rocks; 8. Continental and marine Triassic formations; 10. Jurassic formations of the Mecsek Zone; 11. Jurassic - Lower Cretaceous formations of the Villány Zone; 12. Mecsekjános Basalt Formation (Lower Cretaceous); 13. Upper Cretaceous formations of the Villány Zone; 14. Flysch (Cretaceous-Palaeogene); 19. Lower Miocene continental formations (Eggenburgian-Ottnangian); 20. "Lower rhyolite tuff" and brown coal (Ottnangian); 21. Middle Miocene basal layers (Karpatian - Lower Badenian); 22. Middle Miocene basin formations (Karpatian-Lower Badenian); 24. Middle Miocene andesite (Karpatian, Middle Badenian); 25. Middle Badenian formations with coal; 26. Upper Miocene basal layers (Upper Badenian, Sarmatian, Pannonian); 27. Upper Miocene basin formations (Upper Badenian, Sarmatian, Pannonian); 28. Upper Miocene delta front sediments; 29. Upper Miocene formations with lignite; 30. Pliocene and Quaternary formations; I., Unconformity; II., Fault; III., Juvenile reverse fault

1,800–3,300 m by the wells for instance in the areas of Szarvas, Endrőd, Gyoma, Dévaványa, Túrkeve, Körösladány, Köröstarcsa, Szeghalom, Földes, Biharnagybajom, Ecsegfalva and Bagamér.

They appear in the Derecske–I well, however, in a much deeper position at a depth of nearly 5,000 metres. Their thickness usually is not known, as most of the drilling operations were abandoned in these metamorphic rocks. Only the Túrkeve Te–19 and the Endrőd En-É–6 wells intersected metamorphic rocks in a thickness of 179, and 79 m, respectively, but above Mesozoic formations.

A part of the Variscan metamorphic rocks consists of the high grade metamorphites of the Sarkadkeresztúr Complex. They are made of lineation structure light grey diatexite and occasionally porphyroblastic granite. From the north–north-east and south–south-west it is accompanied by gneiss–mica schist edges with amphibolite intercalations. Their thickness in the Körösladány Köl–4 well exceeds 773 metres.

The other group of the Variscan metamorphic rocks includes high and medium grade metamorphites of the Körös Complex. They were explored in a thickness of 35–210 m in the wells among others in the Szarvas, Endrőd, Gyoma, Dévaványa, Túrkeve, Körösladány, Földes and Kaba areas. Their main mass is an alternation of gneiss and mica schist, with amphibolite, seldom leptinolite (medium grade metamorphosed acidic tuff) intercalations. Discontinuous migmatite or granite bodies lie in the axial zone of the complex with altered eclogite traces. The granitoide bodies occur in an average width of 5–10 km and length of 15–25 km. They are from porphyroblastic biotite granite–granodiorite at Füzesgyarmat. The age of the metamorphic rocks and granitoids is 270–305 million years in the eastern part of the Tiszántúl according to the K–Ar radiometric ages and 329–350, or 400–450 million years more towards the west, based on Rb–Sr dating (SZEDERKÉNYI 1998).

In a small extension in the Endrőd-window area and in the north-east of Bagamér the pre-Cenozoic basement consists of Mesozoic low grade metamorphic rocks, which contacting the Variscan metamorphites along nappe boundary. In the latter site the Bam–1 well intersected anchimetamorphic Middle Triassic calcareous shale and limestone below 2,848 m down to the bottom of the well in 652 m thickness. They could be correlated with the Mesozoic low grade metamorphic rocks known from the Villány–Bihor Unit and from the Barcs-Ny–2, –7,–9 wells drilled in the Dráva Basin.

A Mesozoic strip is situated to the south of the zone of the Variscan metamorphic rocks, in parallel with the Cenozoic and Mesozoic second-order reverse faults, ranging from Szentes to Vésztő in an anticline. In the Mesozoic strip Triassic, Jurassic and Cretaceous formations follow as we go from the north to the south. This zone is a part of the Villány structural belt which is not affected by the Alpine metamorphism significantly.

The Jakabhegy Sandstone Formation which deposited in Early Triassic fluvial and delta environment forms the basement in an ENE–WSW direction strip in the southern neighbourhood of the Variscan metamorphites delineated by tectonic zones, for instance in the Gyoma Gyo–1 well from 3,451 metres down to the bottom of the well (3,500 m). The extension of the Lower Triassic formations is interspersed in smaller patches by Middle Triassic sedimentary rocks deposited in shallow sea. Such as the Anisian Rókahegy Dolomite Formation, consisting of marly dolomite with littoral patch-reefs and oolitic sand banks formed in the open shelf, and the tidal zone. These formations lie at Örménykút (Örm–I well) below 3,945 metres in a thickness of at least 207 metres. The Ladinian Csukma Formation consisting of open-water and lagoon transient facies thick-bedded limestone and dolomite, as well as thin-bedded marly dolomite was identified at Köröstarcsa, in the Köt–I well below 3,346 metres down to the bottom, to 3,401 metres.

To the south from the Triassic basement area, in a similar, relatively narrow, ENE–WSW direction strip of Lower–Middle Jurassic sedimentary formations are bordered by tectonic zones. The material of the Hosszúhetény Calcareous Marl Formation was deposited during the Early Jurassic in shallow sublittoral, and shallow bathyal environments (for instance at Túrkeve). The marly sediments of the Óbánya Aleurolite Formation were deposited in anoxic, shallow bathyal conditions, which can be assumed to be present for instance at Füzesgyarmat (Kovács Zs., Gyuricza ed. 2013b). In the latter place the Lower–Middle Jurassic Komló Calcareous Marl Formation also appears at a depth of 2,043 m, in at least 10 m thickness. This “spotted marl” sequence consisting of alternating layers of bathyal, open-water, bioturbated, ammonitic silty marl, calcareous marl and clay-bearing limestone is a typical formation of the northern edge of the Tethys Ocean (Budai, Konrád 2011).

The layers of the Dorogó Calcareous Marl Formation consisting of marl, argillaceous marl and cherty calcareous marl, and the thin-bedded cherty limestone, radiolarite, and the rocks with chert lenses of the Fonyászó Limestone Formation were formed during the Middle Jurassic in deep bathyal, pelagic environment. These sediments were deposited in the so called “starved” sea formed through the diminishing inflow of debris as the Penninic Ocean widened, where pelagic lime mud was deposited in deep-water, and siliceous mud and radiolarite deposited around the calcite compensation depth (Budai, Konrád 2011).

In the course of the Upper Jurassic – Lower Cretaceous layers of the Pusztaszőlős Marl Formation were deposited in the basin and on the slope, consisting of marl with Calpionella and Lombardia, calcareous marl, limestone, in the upper section clay marl, calcareous marl, limestone and turbidite sandstone. The Endrőd En–7 well intersected it below 2,804 metres down to the bottom of the well in a thickness of more than 415 metres. Jurassic formations were also identified at Tiszakürt from the Tkürt–1 well below 2,675 m, at least in a 125 m thickness. Middle–Upper Jurassic formations were identified in the Örménykút Örm–I well in 74 m thickness overlying the Rókahegy Dolomite Formation.

Occasionally, mainly in the western and north-western part of the area, accompanying the zone of the metamorphic rocks and the older Mesozoic sedimentary rocks, and contacting them along tectonic boundaries, the basement is set up by Lower Cretaceous basic volcanics, and marine sediments developed from basic volcanics by redeposition. They were pushed onto the flysch of the Nádudvar Complex along a second-order Cenozoic reverse fault. The submarine volcanic, and subordinately subvolcanic intrusive rocks of the Mecsekjános Basalt Formation are created by differentiation of picritic basalt magma and ranging from the alkaline basalt through trachybasalt and tephrite up to phonolite. The submarine rift volcanos were probably active in multiple stages during the Berriasian–Hauterivian. The largest observed thickness of the formation on the Great Hungarian Plain exceeds 300 metres. It is deposited at Mezőtúr in the Mtúr–3 well from 2,806 metres down to the bottom of the well in 594 m thickness, and forms the pre-Cenozoic basement in the NE part of the area around Bagamér. The diverse grain-sized sedimentary sequence of the Magyaregregy Conglomerate Formation, erratically changing both in terms of time and space, was formed by the redeposition of volcanics during the Valanginian–Barremian. Abrasion gravels, occasionally atoll carbonates were formed on the volcanic slopes, in the further parts of the volcanic slopes sandy marl layers with tuffaceous marl and calcareous marl intercalations. The thickness of them most probably does not exceed 100 metres, and it contacts occasionally with the rudistid limestone, calcareous sandstone and silt layers of the Nagyharsány Limestone Formation, formed on the Lower–Middle Cretaceous shallow-water platform of the Villány–Bihor Unit. Fauna-free Mesozoic clastic and carbonate formations also occur in several places, which cannot be classified stratigraphically according to the information available up to date. In the compressive stages of the Alpine orogeny associated with crustal shortening, high thickness Mesozoic sequences fell victim to erosion.

In a couple of wells Palaeogene flysch, the material of the Nádudvar Complex was also identified, consisting of cyclically alternating layers of deep-sea (bathyal) sandstone-stripped, sandstone-bedded marl, clay marl and fine-grained sandstone (Nagymarosy 1998). It was identified in nearly 430 metres thickness at Tiszakürt (Tkürt–2 well) below 2,246 m, above Jurassic layers.

Basin fill formations

The rocks constituting the basement were overlaid after substantial denudation and with a sedimentary gap by the Miocene formations, which thicken on the wings of the pre-Cenozoic elevations, but are thin or missing in the top zone of the elevations.

Due to lateral displacements in the Early and Middle Miocene small sedimentary basins were formed with deep troughs of dilatation origin. During the Eggenburgian mainly denudation, or syn-sediment and epigenetic sediment accumulation was characteristic for the area. At this time the sediments of the Madaras Formation consisting of alternations of red (variegated) clay, silt, sandstone and conglomerate were deposited in continental, fluvial environment. These frequently overlie the Körös Complex; their thickness is in the Dévaványa and Endrőd areas 30–170 m, at Füzesgyarmat at least 290 m, reaching 367 metres at Mezőtúr as well.

The syn-rift tectonics caused significant changes to the area (Fodor et al. 1999), and during the Karpatian–Sarmatian the troughs determining the contemporary geological structure were started to evolve: the Vésztő Trough, Komádi–Mezősas Trough, Derecske Trough. The SW–NE direction basement elevation series, characteristic for the recent surface of the pre-Cenozoic basement, was formed as a result of the structural development by thrusts, reverse faults and nappes, plus the north-west–south-east transverse fault system. The elevations run in a depth between 1,500 and 2,500 m for instance at Füzesgyarmat, Martfű, Dévaványá, Endrőd, Túrkeve and Biharnagybajom. The major depressions between elevations can be found in a depth of 3,000–3,500 m at Körösladány, exceeding 4,000 metres at Túrkeve, Füzesgyarmat, Endrőd and Dévaványa, and 6,000 metres at Konyár in the Derecske Trough. The argillaceous marl and silt layers of the Kiskunhalas Formation deposited in open-water and intercalated by sandstone, gravel, tuff and tuffite in the depressions and troughs, for instance in a thickness of 80–220 metres at Endrőd, and 240 metres at Öcsöd. The layers of the Budafa Formation consisting mainly of sand and conglomerate were formed on the shorefaces.

The trough formation following the compression phase at the boundary of the Karpatian and the Badenian stages was followed by a short volcanic episode. At this time beside the subvolcanic andesite (Hasznos Andesite Formation) generated in the North Hungarian Mountains, the pyroclastic tuff creating the Tar Dacite Tuff Formation ("Middle rhyolite tuff") affected a substantial area. This tuff is 46 m thick under 2,622 m depth at Endrőd. The Early Badenian coarse-grained clastic Abony Formation interfingers with volcanics or appears alone, consisting of basal breccia and conglomerate, and then a sequence refining upwards, transiting into sandstone, frequently with tuff and tuffite layer intercalations. Its thickness in the Endrőd area reaches 250 metres.

During the Badenian open-water, offshore, and basin facies cyclical foraminiferal clay marl, marl and silt were deposited in the deep zones of the Great Hungarian Plain area. These sediments were previously classified into the Makó Formation (its thickness at Endrőd is 40 m, at Füzesgyarmat 71 m). Sporadically the littoral abrasion coarse-grained clastic, nearshore clastic and calcareous sediments of the Pusztamiske Formation also occur, occasionally with tuff and tuffite intercalations. This coarse-grained clastic sequence is 45–305 m, 118 m, and 120 m thick at Szeghalom, Endrőd, and Mezőtúr, respectively. In the wake of the rising sea level in the Late Badenian a shallow-marine carbonate ramp was evolved, along its broken shoreface the wildlife was highly diverse (Budai, Konrád 2011). The biogenic Lajta Limestone Formation developed there is extremely rich in fossils, featuring mainly bivalves (different Pectens and Cardiums), snails (Turritella, Corbula, Aporrhais, Gibbula etc.), as well as small and large Foraminifera (Heterostegina), echinoids (Clypeaster), bryozoa, red algae (lithothamnium). Basal conglomerate, breccia and sandstone also belong to it. Its thickness varies even in wells next to each other, caused partly by the bottom equalising effect of the reef limestone. It is found in deeper structural position at Körösladány (below 2,640 and 2,726 m) in a thickness of 87 and 64 m, at Szeghalom it is in higher position (below 1,878 and 2,033 m) in a thickness of 234 and 17 metres. The clastic succession of the Ebes Formation was formed at the same time, intersected by the wells in the surrounding of Köröstarcsa and Szarvas below a respective depth of 3,292 and 3,439 m in more than 40 m thickness, and is assumed to be present in the Derecske Trough as well (Kovács Zs., Gyuricza ed. 2013a). The foraminiferal clay marl, and silt-bearing clay succession of the Szilágy Clay Marl Formation, containing occasionally thin sandstone and tuff intercalations, were formed in shallow neritic environment, often interfingered with the Lajta Limestone Formation (for instance at Túrkeve).

The sporadic, patchy appearance of the Sarmatian formations in the area can mostly be attributed to the large scale denudation and erosion preceding the Late Miocene. The molluscan clay, clay marl, subordinated sand, calcareous marl, calcareous sandstone (the so-called "Cerithium limestone") layers of the Kozárd Formation deposited in brackish water, shallow-sea–nearshore environment occur primarily in the Martfű–Mezőtúr–Túrkeve zone, but they were identified in certain Endrőd and Dévaványa wells as well. Their thickness is 10–80 m. (In the southern neighbourhood of the area, in the

Hunya–1 well transgressive, littoral abrasion, brackish breccia, conglomerate and sandstone layers of the Dombegyháza Formation also occur in more than 112 m thickness.)

Following the formation of the Lake Pannon some 12 million years ago by isolation from the world ocean (Kázmér 1990, Magyar et al. 1999) the Békés Conglomerate Formation consisting of abrasion conglomerate, sandstone, and seldom breccia deposited on the basement during transgression, for instance in the Gyoma Gyo–1 well below a depth of 3,388 metres, in a thickness of 33 metres. Directly on the basement or above the Békés Conglomerate the Endrőd Marl Formation with high organic matter-containing calcareous marl – argillaceous marl succession can be found. The marls deposited in the inside of the basin under different water depth varying from a couple of metres to hundreds of metres in a so-called “starved” basin. The lowest part of the formation is made up by the hemipelagic calcareous marl and marl, the so-called basal marl of the Tótkomlós Calcareous Marl Member in a thickness varying between 12 and 218 metres. They gradually transform into the deep-water (hemipelagic) Nagykörű Clay Marl Member (Juhász 1994), and are overlaid by the distal turbidite layers of the Vásárhely Marl Member. The formation currently sits mostly in a depth between 2,000 and 3,000 metres, somewhat higher at Szeghalom, and deeper than 3,000 metres in the Köröstarcsa Köt–I and the Örménykút Örm–I wells, with a thickness ranging from a couple of ten metres up to a couple of hundred metres (at Körösladány and Örménykút it is approximately 330 m, at Szeghalom in the Sz–41 well 475 m thick).

The filling up of the Lake Pannon in the eastern part of the Great Hungarian Plain took place from the north-east (Vakarcs, Várnai 1991, Juhász 1992, Juhász et al. 2006), while the surrounding of Dévaványa and the plains to the west were also reached by large delta systems arriving from north-western direction (Juhász et al. 2006, Thamóné Bozsó et al. 2006).

A part of the sedimentary material transported from the shelf edge to the deep basin was deposited in the form of turbidites. This is how the Szolnok Sandstone Formation (Figure 4.6.2–4.6.4) developed, which is set up beside thick turbidite succession at least in half from pelite deposited in the periods between turbidity currents, with fine sand body intercalations ranging from a thickness of 1–2 metres up to 10–20 metres. The formation is thinned out frequently from the deeper parts of the basin towards the edges, its thickness varying in the area from a couple of 10 metres up to more than 1,100

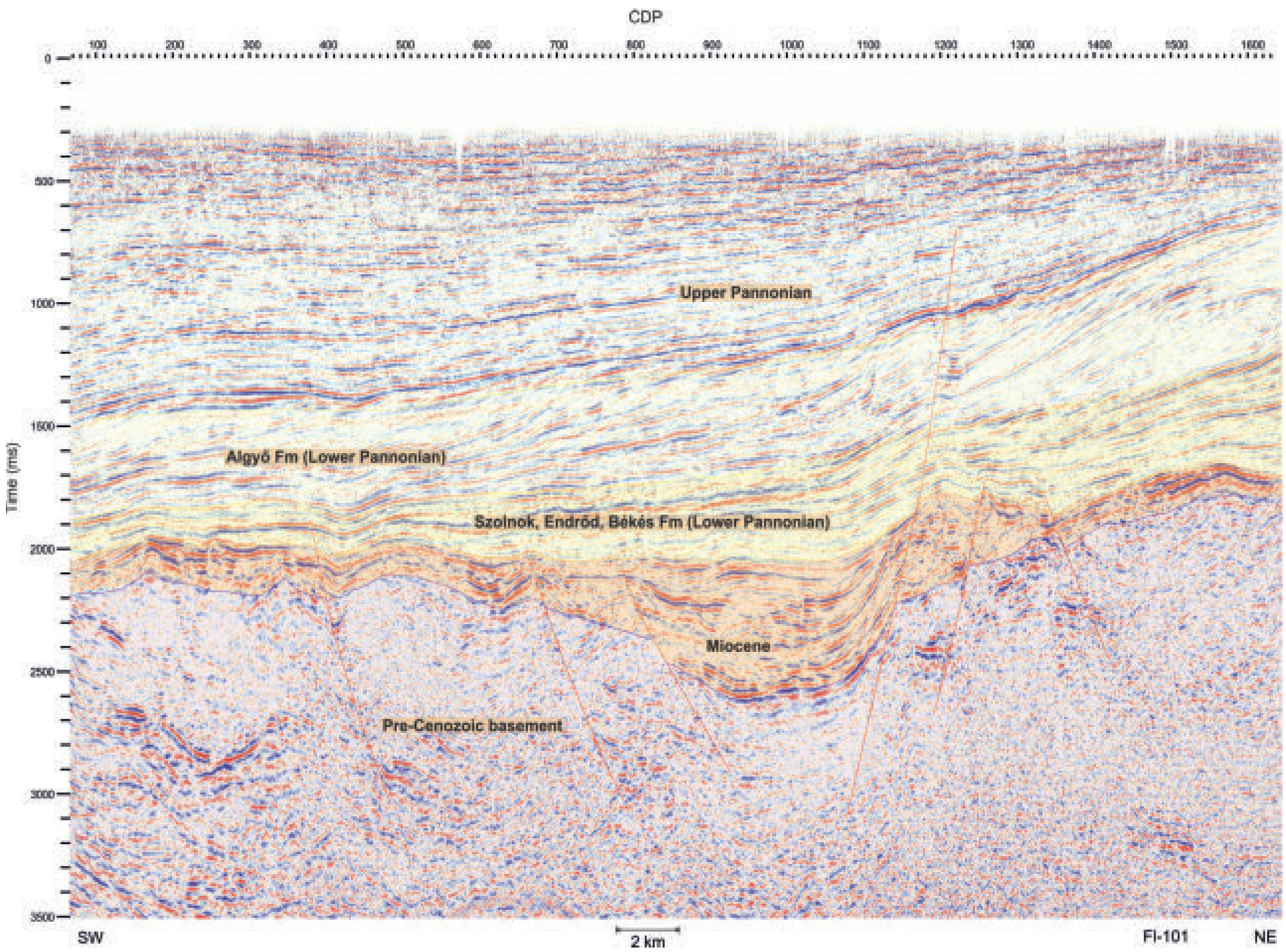


Figure 4.6.2. The Fl-101 seismic section running in SW-NE direction between Túrkeve and Füzesgyarmat (the trace line of the profile can be seen on Figure 4.5.1., the red lines indicate the faults)

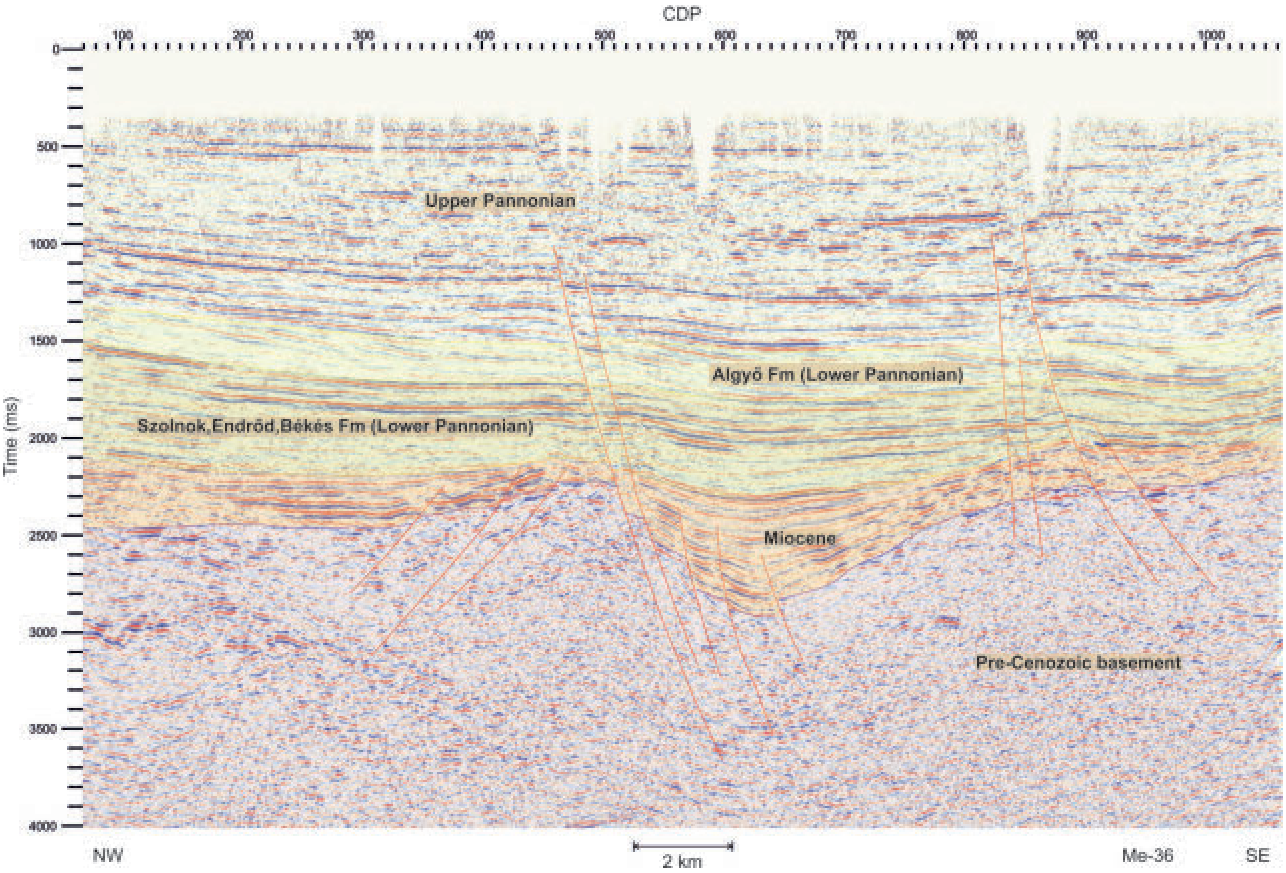


Figure 4.6.3. The ME-36 seismic section running in the north-west-south-east direction at Mezőtúr (the trace line of the profile can be seen on Figure 4.5.1., the red lines indicate the faults)

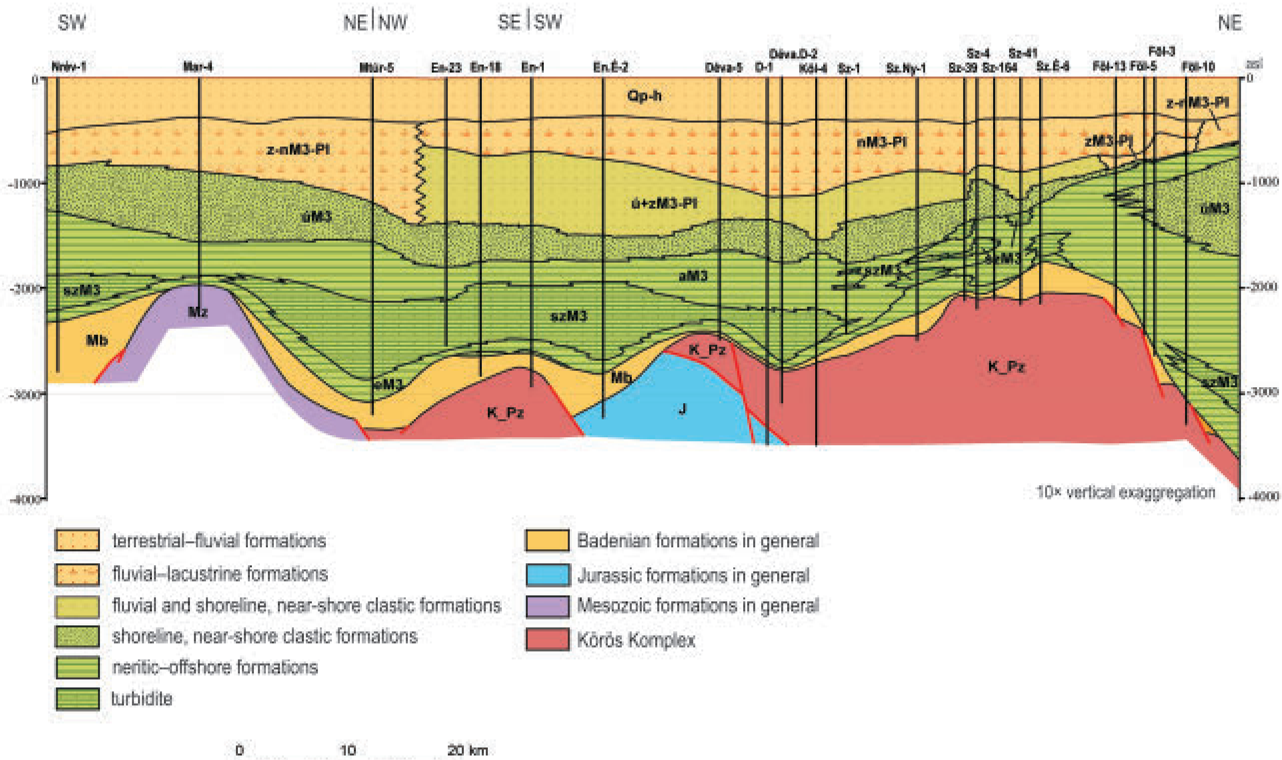


Figure 4.6.4. Geological section running in SW–NE direction on the area (Mining and Geological Survey of Hungary)

Legend: K-Pz: Körös Complex, Mz: Mesozoic formations, J: Jurassic formations, Mb: Badenian formations, eM3: Endrőd Marl Formation, szM3: Szolnok Sandstone Formation, aM3: Algyő Formation, úM3: Újfalu Sandstone Formation, zM3: Zagyva Formation, nM3-Pl: Nagyalföld Variegated Clay Formation, Qp-h: Pleistocene and Holocene formations

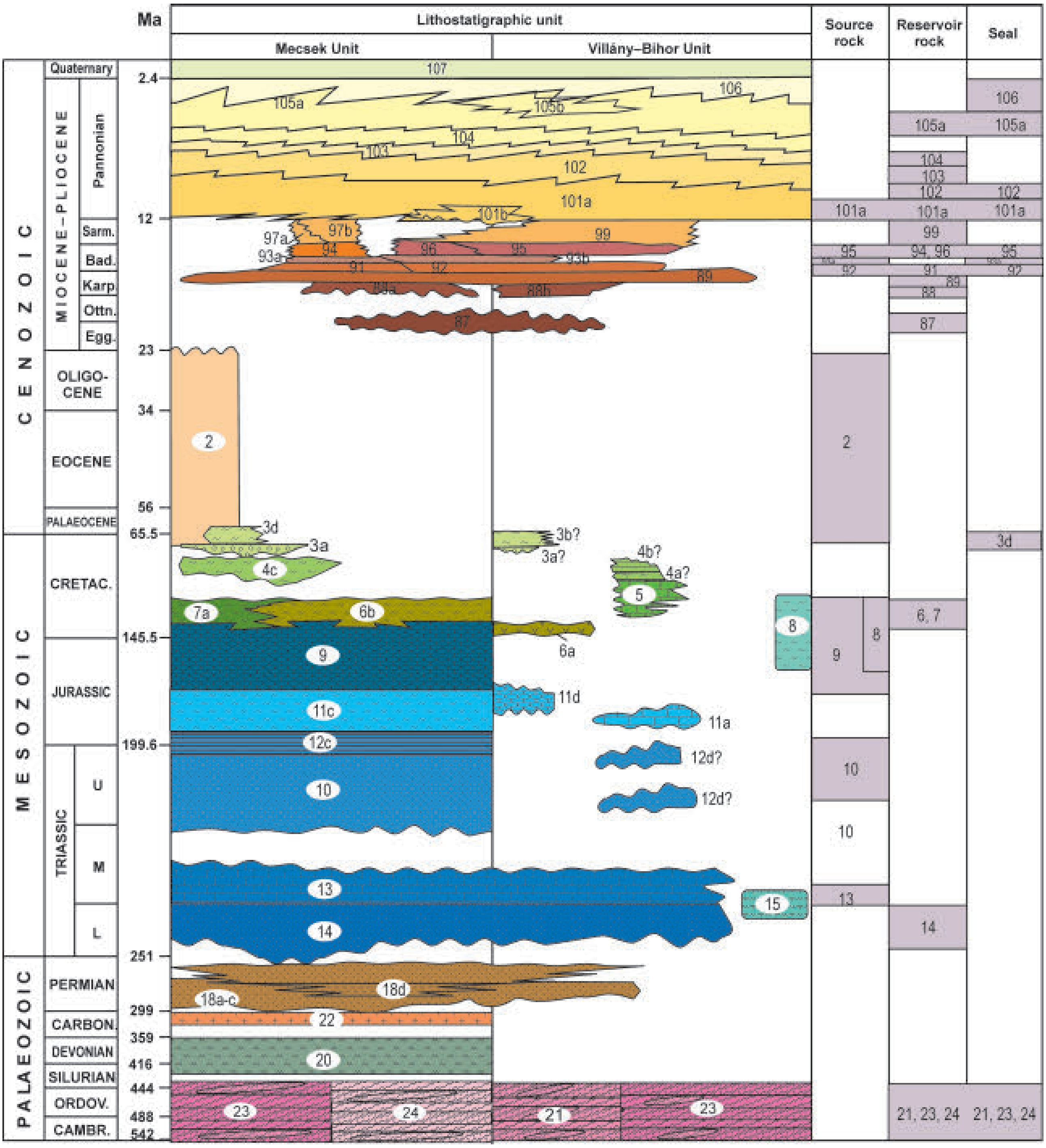


Figure 4.6.5. Theoretical stratigraphic column and the elements of the hydrocarbon systems of the southern part of the Nagykunság area

Legend: 2. Senonian–Palaeogene flysch; 3a Senonian terrestrial, fluvial conglomerate, breccia; 3b Senonian bathyal marl, sandstone, conglomerate; 3d Senonian deep-marine (bathyal) marl; 4a Albian basin facies marl and clastic slope sediments; 4b Middle Jurassic bathyal slope clastic sediments; 4c Upper Jurassic basin facies marl; 5. Lower Cretaceous platform limestone; 6a Lower Cretaceous basic volcanics; 6b marine sediments redeposited from Lower Cretaceous basic volcanics; 7. Lower Cretaceous pelagic marl, limestone; 8. Jurassic – Lower Cretaceous pelagic limestone, marl; 9. Middle Jurassic – Lower Cretaceous pelagic limestone, cherty limestone, calcareous marl; 10. Lower–Middle Jurassic pelagic, fine-grained siliciclastic succession; 11a Lower Jurassic shallow sublittoral limestone; 11d Middle Jurassic shallow bathyal limestone; 12b Upper Triassic fluvial, delta, lacustrine siliciclastic succession; 12c Upper Triassic – Lower Jurassic fluvial, coastal succession with coal; 12d Upper Triassic shallow-water siliciclastic–carbonate succession; 13. Middle Triassic shallow-marine, siliciclastic and carbonate succession; 14. Lower Triassic fluvial and delta siliciclastic formations; 15. Mesozoic low grade metamorphic rocks; 18a-c Permian terrestrial, fluvial and lacustrine clastic succession; 18d Upper Permian – Lower Triassic fluvial clastic succession; 20. Lower Palaeozoic low grade metamorphic rocks; 21. Variscan medium grade metamorphic rocks (gneiss, mica schist, marble); 22. Variscan granitoid rocks; 23. Variscan metamorphic rocks (gneiss, mica schist, amphibolite); 24. Variscan crystalline rocks without subdivision; 87. Lower Miocene terrestrial, fluvial red clay, siltstone, sandstone, conglomerate; 88a Karpatian shoreface sand, conglomerate; 88b Karpatian open-water argillaceous marl, siltstone; 89. Karpatian, mainly airfall dacite tuff; 91. Lower Badenian abrasion basal breccia; 92. Badenian open-marine clay, clay marl; 93a Badenian pelagic clay marl, marl; 93b Badenian nearshore gravel, conglomerate, sandstone; 94. Middle Badenian shallow-marine biogenic limestone; 95. Upper Badenian open-marine clay, clay marl; 96. Upper Badenian shallow-marine, biogenic limestone, conglomerate; 97a Sarmatian coastal abrasion breccia, conglomerate, sandstone; 97b Sarmatian shoreface, nearshore limestone, sandstone, marl; 99. Sarmatian shallow-marine clay, clay marl; 101a Pannonian abrasion conglomerate, sandstone; 101b Pannonian open-water lacustrine calcareous marl, marl, clay marl; 102. Pannonian deep-water turbidite succession; 103. Pannonian sediments deposited in underwater slope environment; 104. Pannonian littoral siliciclastic succession; 105a Pannonian fluvial and lacustrine siliciclastic succession; 105b Pannonian variegated clay with lignite deposited on delta plain; 106. Pannonian fluvial siliciclastic succession; 107. Quaternary sediments

metres, is located in a depth between roughly 1,300 and 4,100 m, it is in the deepest position in the surroundings of Derecske, Örménykút and Szarvas.

The grey clay-bearing silt containing sequence with thinner or thicker sandstone intercalations of the Algyő Formation was developed on the delta slopes and basin slopes of the Lake Pannon, mainly in the sediment transport channels. The highest thickness of the Algyő Formation in the area is 1,000–1,100 m, which is reached in the Derecske Trough and the vicinity of Földes. Due to the progradation of the slope, the age of the formation is getting younger from the NE and NW to the south.

The Újfalu Sandstone Formation consisting of frequently alternating layers of mainly fine- and medium-grained sandstone, sand, silt and clay marl, formed on delta front, delta plain and coastal plain with much carbonised plant remnants, and frequently lignite layers. Based on the drilling successions the thickness of the formation in the area varies mostly between 100 and 500 metres, but occasionally it exceeds this substantially, for instance in the Gyoma Gy–1 well and in the Derecske–I well it is 828 m and 1,195 m thick, respectively.

The sediments of the Zagyva Formation deposited on fluvial–flood plain, lacustrine and paludal environments in the background of the prograding deltas. It consists of frequent alternation of grey, bluish-grey silt – argillaceous marl – sandstone, occasionally with variegated clay and lignite intercalations, seldom marl balls. Very diverse sediments belong here; depend on the part of the fluvial plain where they were formed. The deposition of the formation started at the end of the Miocene and extended over to the Pliocene significantly (CSÁSZÁR ed. 1997). In many places it can only be distinguished from the Újfalu Formation with great difficulty, or not at all. Its thickness in the area varies between a couple of ten metres and hundreds of metres, in the vicinity of Szarvas (for instance in the Szr-DNy–1 well) nearly 800 metres.

The grey and variegated clay layers of the Bükkalja Lignite Formation were formed on delta plains. This formation also contains sand and lignite intercalations, its thickness for instance at Mikepércs is 211 m.

Following the filling up of the Lake Pannon the area subsided further and fluvial succession was formed with significant thickness. The Nagyalföld Variegated Clay Formation consists of alternating bluish grey sand and spotty, variegated clay layers deposited in lacustrine–fluvial environment, with frequent intercalations of lignite and gravelly sand layers, which were assumed to be formed up to the beginning of the Pleistocene. Its thickness varies mostly between 100 and 700 m, but in certain wells at Szarvas and Örménykút (Szr-DNy–2, –3, Örm–I) exceeds 800 metres. It is difficult to distinguish from the Zagyva Formation, according to JÁMBOR (1989) lignite intercalations are less frequent in the Nagyalföld Variegated Clay Formation, however according to JUHÁSZ (1998) the palaeosoil horizons are more common in the Nagyalföld Formation than in the Zagyva Formation.

Mainly fluvial sand, silt, clay, subordinately gravel and infusion loess were formed in the Pleistocene. The fluvial succession is very diverse, consisting of sand dominated sediments of channels and point bars, and clay-bearing flood plain formations. The Pleistocene sediments were found in the greatest thickness in the Szarvas and Dévaványa wells (490–607 m). In the Holocene, mostly fluvial clay and silt were deposited, but occasionally fine-grained lacustrine sediments and peat were formed as well (for instance at Szeghalom). The neotectonic investigations (BADA et al. 2007a) suggest that the transtensional stress field formed in the area during the Miocene still exists continuously up to date, in spite of the slowed down basin-scale subsidence of the basement, therefore the strike-slip displacements combined with normal faults acted practically up to the surface.

The schematic stratigraphic column and the elements of the hydrocarbon system of the southern part of the Nagykunság area are shown on Figure 4.6.5.

An overview of hydrocarbon geology

The hydrocarbon accumulations in the area are situated arranged mostly in NE–SW direction, mainly above the pre-Cenozoic basement elevations (Figure 4.5.8).

Source rocks

The main potential source rocks in the area are the pre-Pannonian Miocene and the Lower Pannonian pelites, but certain Mesozoic, and Upper Cretaceous – Palaeogene rocks may also be assumed to have a capacity to generate hydrocarbon.

Among the pre-Neogene potential source rocks the greenschist and amphibolite facies metamorphic rocks have lost their hydrocarbon potential due to their metamorphism suffered in the Hercinian orogenic phase, which is indicated by the results of the vitrinite reflectance measurements carried out on the materials of the Köröstarcsa Köt–I and Körösladány Köl–1 wells, and south of the area the Doboz–I well. The hydrocarbon generating potential of the Mesozoic sediments is not yet clarified entirely. They might have become source rocks during the Miocene by rapid subsidence and burial (DANK 1988), but according to their lithology they are not thought to be significant source rocks in this area. The substantial quantity of organic matter and sapropelic allochthon bitumen of the Triassic pelites are currently in the stage of dry gas formation according to their vitrinite reflectance values. At some places, for instance in the Endrőd North area it can be assumed that the Lower Jurassic pelitic beds might have generated hydrocarbon as well (BONCZ et al. 1994). A part of the

Upper Cretaceous – Palaeogene flysch might also be source rock (Szentgyörgyiné et al. 2011c), and the pelitic carbonate rocks of this age, as well as the clastic sediments partly deposited on the shelf are also in the main oil generation phase according to their vitrinite reflectance (R_0) values.

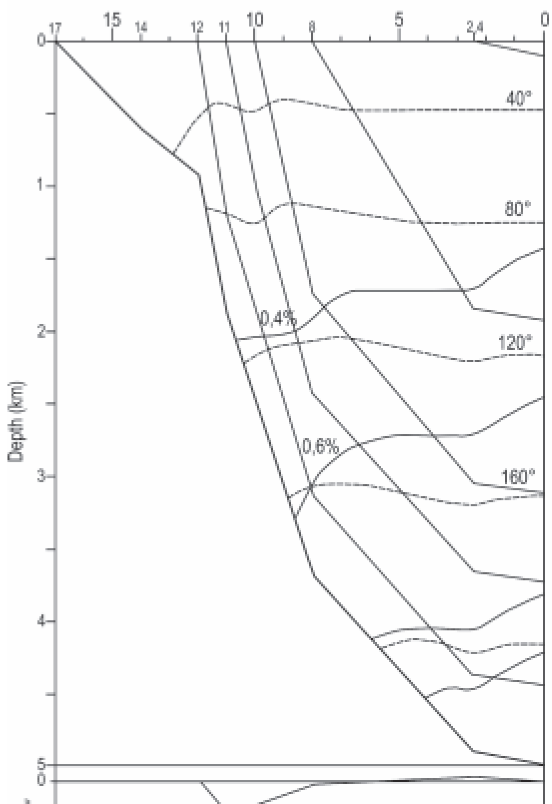
The pre-Pannonian Miocene formations in the Derecske Trough can be found in the dry gas generation zone according to the results of the complex geochemical and vitrinite reflectance measurements of the Derecske–I well (Horváth et al. 1988). Based on the dispersed organic matter content of the Badenian pelitic carbonate rocks (occasionally 5 weight %), and their total organic carbon content (TOC) they can be classified as potential source rocks (Clayton et al. 1994a), their vitrinite reflectance indicates thermal maturity, although they have small thickness on the geochemical supply area. The extension and maturity of the Miocene source rocks in the Great Hungarian Plain is shown on Figure 4.5.10 adapted from Badics, Vető (2012).

The Lower Pannonian sedimentary succession has got over the main phase of oil generation as demonstrated by the data derived from the analysis of the Derecske–I well (Horváth et al. 1988, Figure 4.6.6). The TOC level of the Endrőd Marl Formation Tótkomlós Calcareous Marl Member which has been generated under varied water depth conditions reached 2 wt% (Clayton et al. 1994a), which is ranked it as a potential source rock. It is currently in the oil window, and in the deep basins in the wet gas zone.

Based on vitrinite reflectance data of the Gyoma–1 well among the local source rocks the Lower Pannonian prodelta and open-water marls are in the oil generation zone.

The thick, predominantly pelitic Lower–Middle Miocene and Pannonian sedimentary succession of the deep Neogene basins is in the most favourable position from the perspective of hydrocarbon generation, demonstrated by the burial history model of the Körösladány Köl–1 well (Figure 4.6.7). These potential source rocks are marine and lacustrine sediments deposited under anoxic conditions. Their organic matter derived primarily from terrestrial source. Results of the Rock-Eval pyrolysis analyses suggest that they contain mainly Type III kerogen, which is gas generating, or mixed gas/oil generating, as well as subordinately Type II kerogen (Clayton et al. 1994a). In the Túrkeve–Vésztő area the Middle Miocene (Badenian) and Lower Pannonian source rocks generated variable maturity oil as a function of the depth, pressure and thermal history (Szabó et al. 2011). A part of the oil accumulated in the structural elevations were not generated at a temperature corresponding to the top of the oil window, but at a somewhat lower temperature, therefore it is immature early oil (R_0<0.4–0.6%). The other part of the oil was generated at high temperature and is very mature (R_0>0.6–0.9%, Szentgyörgyiné et al. 2010).

Based on the results of analysis of the Derecske–I and the Beru–4 wells, the Derecske Trough is the deep basin with the



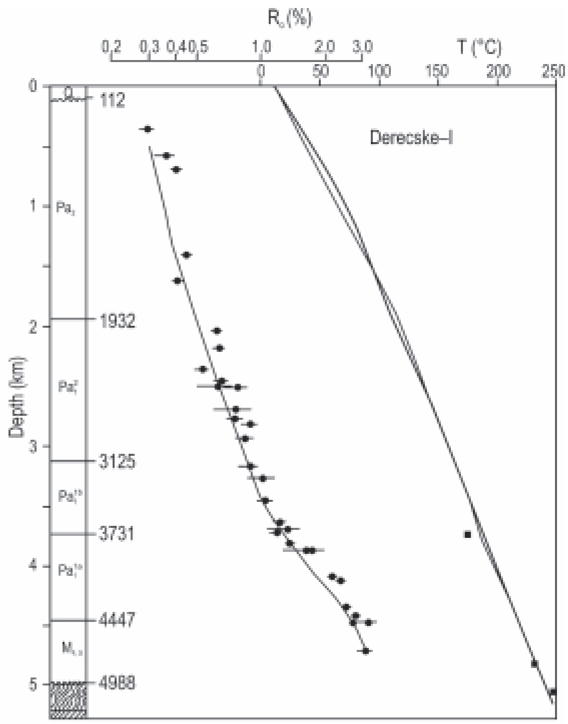


Figure 4.6.6. Burial history model, vitrinite reflectance and temperature values in the Derecske-I well (Horváth et al. 1988)
Legend: hw: water depth at the time of deposition (in metres); R_0: vitrinite reflectance value; M_4: Badenian (17–14 million years); M_5: Sarmatian (14–12 million years); Pa_1^{1a}: 12–11 million years; Pa_1^{1b}: 11–10 million years; Pa_1^2: 10–8 million years; Pa_2: 8–2.4 million years; Q: Quaternary

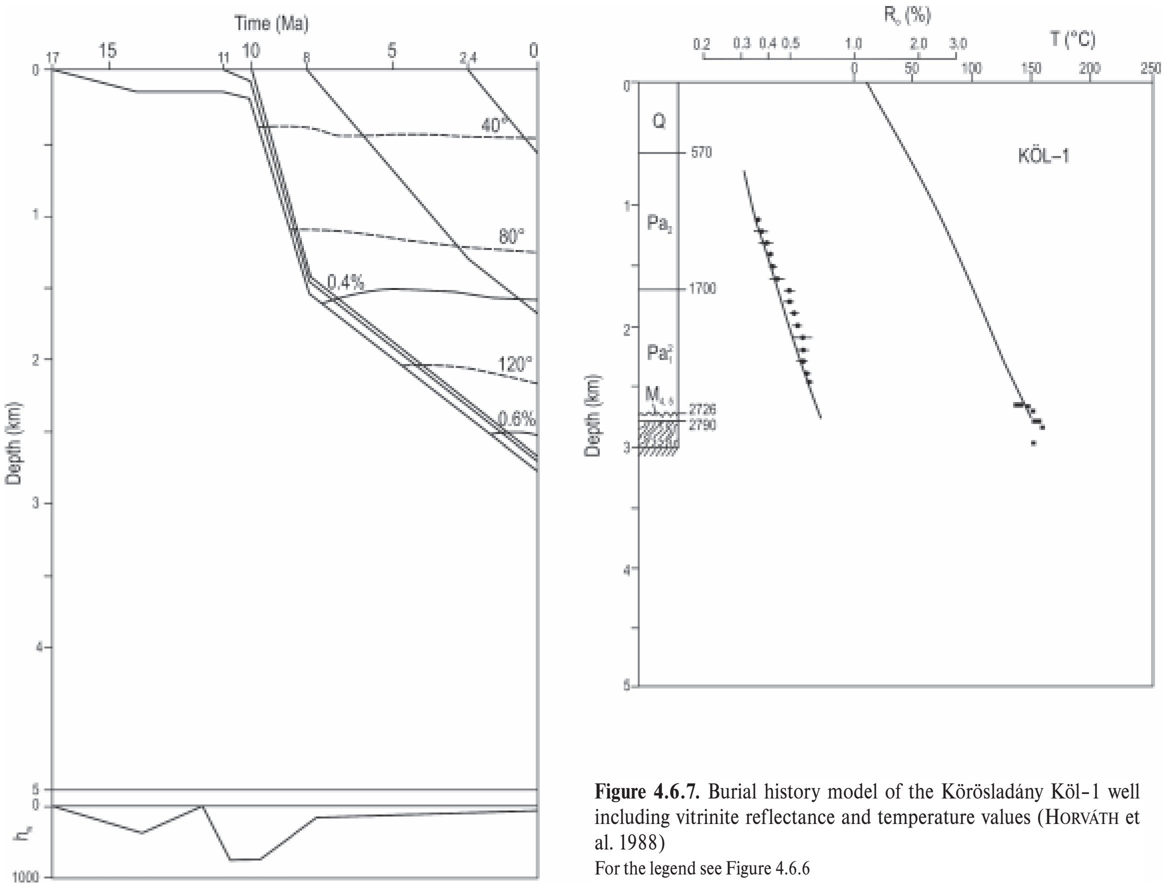


Figure 4.6.7. Burial history model of the Körösladány Köl-1 well including vitrinite reflectance and temperature values (HORVÁTH et al. 1988)
For the legend see Figure 4.6.6

most favourable properties of the Tiszántúl area (SZENTGYÖRGYINÉ et al. 2012b). Here and in the Vésztő Trough alike, the main source rocks are provided by the thick Middle Miocene pelites, and the deep situated Lower Pannonian basal clay marls (Endrőd Marl Formation, SZENTGYÖRGYINÉ et al. 2011).

At the deepest, central part of the Derecske Trough much larger volume of source rocks can be assumed than that discovered by the Derecske–I well, since according to the 3D seismic measurements the potential source rocks thicken towards the depocentre of the Derecske Trough. The hydrocarbon generation started in the Derecske Trough deep zone about 8.5 million years ago in the pre-Pannonian Miocene pelites, and 7.5 million years ago in the Lower Pannonian clay marls and marls (SZENTGYÖRGYINÉ et al. 2011c, 2012c).

Although the fine-grained sedimentary rocks younger than the Lower Pannonian show occasionally quite promising organic matter content, for instance the Upper Pannonian delta plain Újfalu Sandstone Formation has good source rock properties, but due to their shallow burial and low temperature they are not mature enough, their vitrinite reflectance value is less than 0.6%.

Migration

Hydrocarbon migration in the area took and takes place still mainly in the porous sandstones and in the fragmented rocks of the basement, but the tectonic elements, fractured belts, and the sequence boundaries might also play important roles in the migration. The unconformity surface between the Middle Miocene and the Pannonian formations constitutes important migration route, and significant lateral migration routes can be presumed along the sequence boundaries under and above the Újfalu Sandstone Formation, and within the Lower Pannonian (overlying the Pl1–3 sandstone group, GAJDOS et al. 1997d). Migration was assisted by overpressure in many places, which might have resulted from dewatering during compaction, hydrocarbon generation, metamorphism of the carbonate rocks associated with carbon dioxide generation, and from aquathermal warming (SZABÓ et al. 2011).

Early oils migrated only to a small distance, while matured hydrocarbons generated at high temperature transported in a longer path, migrating both laterally and upwards. In the Túrkeve–Vésztő area a vertical migration of 3,500 metres was estimated based on the maturity of the rocks, the carbon isotope composition of methane, and the maturity–depth comparison of the Neogene source rocks (SZABÓ et al. 2011). A part of the natural gas migrated from the south-west, from the deeper parts of the Békés Basin into the traps in the middle part of the area (Szarvas, Endrőd and Dévaványa regions,

Figure 4.6.8). In the reservoirs situating in the structural high zones those hydrocarbons which migrated upward from the deep basin and the less matured oil arriving from a small distance driven by smaller buoyant force were mixed. Due to the amalgamation of the different source hydrocarbons, the composition and the condensate content of the gases might change significantly within a few kilometres for instance in the Túrkeve and Vésztő regions (Szabó et al. 2011).

The hydrocarbons originating from the Neogene source rocks in the Derecske Trough migrated towards the sandstone bodies (Szolnok Sandstone Formation), and following the monotonously ascending morphological position of the sandstone succession towards the edges, reached the edge of the trough. It can be assumed that a part of the natural gas could get from the Miocene and Lower Pannonian source rocks into the Upper Pannonian layers by migration along the faults (Lemberkovics et al. 2005, Windhoffer, Bada 2005).

Methane content of underground waters suggests that the Pannonian conventional gas reservoirs do not constitute a completely closed system, but tertiary migration takes place from them (Nádor et al. 2015). No migration occurs in the thick matured hydrocarbon generating pre-Pannonian Miocene sediments in the SW part of the Derecske Trough because of their low permeability, or there is primary migration only for a very short distance, therefore the generated hydrocarbons accumulated in place, and filled up the available pore space in the source rock.

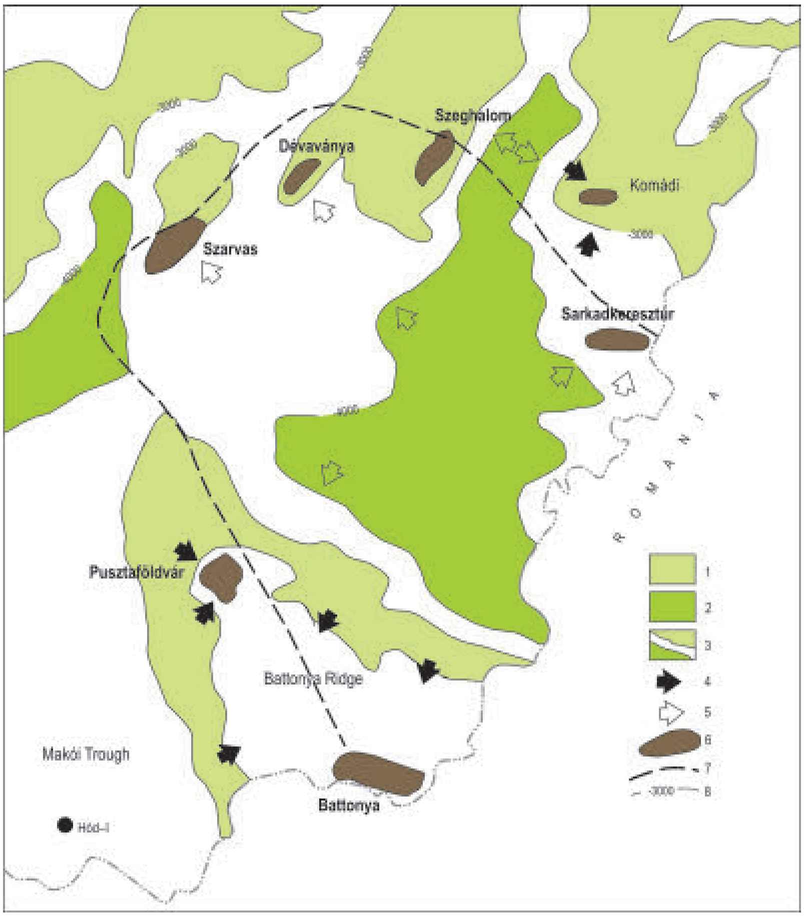


Figure 4.6.8 Hydrocarbon generation areas and migration directions depicted on the map of the base of the Neogene formations (adapted from Clayton et al. 1994a)

Legend: 1. generation zone of least mature oils originating from Miocene source rocks (0.35–0.60% R_0); 2. generation zone of more mature oils; 3. transient area between the previous two maturity zones; 4. direction of the oil migration; 5. direction of the natural gas and the condensate migration; 6. oil and natural gas field; 7. approximate boundary of the Békés Basin; 8. Contour lines of the Neogene basement depth (metres bsl)

Reservoir rocks

The most important hydrocarbon reservoir rocks in the area are as follows:

— fractured, brecciated, cataclastic metamorphic rocks, mainly gneiss and amphibolite in the basement (Sarkadkeresztúr Complex, Körös Complex),

— Lower Triassic sandstone (Jakabhegy Sandstone Formation),

— Middle Triassic limestones, dolomites, dolomite breccia (for instance Csukma Formation, Rókahegy Dolomite Formation),

— Lower Cretaceous diabase agglomerate (Mecsekjános Basalt Formation, Magyaregregy Conglomerate Formation),

— Lower Cretaceous limestones (for instance Nagyharsány Limestone Formation),

— Lower Miocene conglomerate, breccia (Madaras Formation),

— Lower Miocene conglomerate (Budafa Formation),

— pre-Pannonian Miocene tuff, tuffite (for instance Tar Dacite Tuff Formation),

— Middle Miocene (Badenian) sandstone, clay-bearing, tuffaceous silty sandstone (Abony Formation),

— Middle Miocene (Badenian) limestones (Lajta Limestone Formation, Ebes Formation),

— Middle Miocene (Sarmatian) sandstone, tuffaceous sandstone, calcareous sandstone, conglomerate, sandy marl (Kozárd Formation),

— Middle Miocene (Sarmatian) fractured marl, calcareous marl, sandy marl (Kozárd Formation),

— Lower Pannonian fractured basal calcareous marl, sandy calcareous marl, sandstone-stripped argillaceous marl (Endrőd Marl Formation, Tótkomlós Calcareous Marl Member, Vásárhely Marl Member),

— Lower Pannonian prodelta turbidite, clay-bearing, and silty sandstone, marly sandstone, clay-bearing sandstone (Szolnok Sandstone Formation),

— Lower Pannonian sandstone, silty sandstone, clay-bearing sandstone deposited in delta slope and basin slope environments (Algyő Formation),

— Upper Pannonian sandstone, silty sandstone, clay-bearing sandstone deposited on delta front and delta plain (Újfalu Sandstone Formation),

— Upper Pannonian – Pliocene clay-bearing, silty sandstone of meandering rivers (Zagyva Formation).

The most important reservoir rocks of the area are the Lower Pannonian formations, primarily sandstones. More than half of the hydrocarbon reservoirs were built up of them. The Lower Pannonian calcareous marls may also be reservoir rocks (for instance Dévaványa, Endrőd North, and Martfű South fields). In a third of the occurrences the Upper Pannonian sandstones accumulate hydrocarbons (certain reservoirs of the Endrőd–III., Hajdúbagos East, Hosszúpályi South, Monostorpályi South-east and East, Sáránd shallow, Szarvas, Túrkeve East fields). Nearly a tenth of the accumulations are situated in pre-Pannonian Miocene reservoir rocks, such as sandstone, clay-bearing, carbonate, tuffaceous sandstone, conglomerate, and breccia which derived mainly from metamorphites (for instance in the Biharnagybajom, Dévaványa, Endrőd North, Földes, Kaba South, Martfű South, Martfű North, Szeghalom fields). Middle Miocene limestone stores hydrocarbons for instance at Körösladány and Köröstarcsa. In the latter location and at Örménykút accumulation occurred in Mesozoic limestone and dolomite. At Martfű Lower Triassic diabase and agglomerate are the reservoirs. Accumulations are found in Palaeozoic metamorphites at Szeghalom.

The fractured, brecciated, cataclastic metamorphic rocks (primarily gneiss and amphibolite) of the basement have secondary porosity, created partly upon tectonic impacts and partly due to onetime sub-aerial weathering; their porosity is 5–8%. The Mesozoic reservoir rocks (quartz sandstone, carbonates, diabase agglomerate) have in general 4–9% porosity. The porosity of the Middle Miocene biogenic limestones varies in the range of 4–14%, that of the sandstones is 8–19%, the tuffaceous sandstones 9–21%, the conglomerates in general 7–12%. The Lower Pannonian sandstone reservoirs are mostly prodelta facies, with a porosity of 9–23%. The Upper Pannonian sandstone, clay-bearing, silt containing sandstone reservoir rocks have the highest porosity between 11 and 30%.

Seal rocks

The seal rocks of the area are set up mainly by the impermeable marls, argillaceous marls and shales. Their thin interbeddings provide local closure, thick layers regional closure. The Lower Pannonian marls, calcareous marls, argillaceous marls, marly silts and shales are the most frequent seal rocks, especially the Endrőd Marl Formation, and its Vásárhely Marl Member for instance in certain reservoirs of the Dévaványa and Füzesgyarmat fields, as well as the Algyő Formation at the Berettyóújfalu field. The thick layers of the Endrőd Formation create a regional closure above the pre-Pannonian Miocene reservoirs. The fine-grained, clay-bearing sedimentary rocks in the lower part of the Szolnok Sandstone Formation, and the 20–50 metres thick argillaceous marl – clay layer at the Pa–4 sequence boundary may also behave as regional seal formations. The Upper Pannonian marls, marly silts, and argillaceous marls are also good seal rocks, for instance in the Endrőd North and Túrkeve West areas, or in the Derecske Trough.

Subordinately impermeable Middle Miocene marls, tuff layered argillaceous marls (for instance in the Földes Northeast field), clastic sedimentary rocks (for instance at Füzesgyarmat) and Upper Pliocene clay seal rocks (for instance in the Derecske Trough) may also occur. What is more, the impermeable parts of the basement metamorphic rocks may also close the reservoirs (for instance in the Szeghalom North field). In the case of lithologic traps closure is caused by the reservoir becoming impermeable, clay-bearing, or thinning out. If the faults and fault zones serving also as migration routes become impermeable, they would close by forming a migration barrier. Occasionally capillary closure can be assumed formed as a result of compaction and diagenesis.

Trapping

Hydrocarbons, migrating away from the source rocks, accumulated in the fragmented, fractured rocks of the basement, in stratigraphic traps as traps formed due to unconformity in the sandstones of anticlines developed due to folding and compaction (DANK 1988, CLAYTON et al. 1994a, HORVÁTH, TARI 1999). Location, size and morphology of traps is influenced by the basement morphology, local maximums, the overlying pseudoanticlines, the impermeability originating from lithological shift, thinning and pinching out of the reservoir rocks, the closing effect of the faults, the capillary pressure conditions, and the pressure systems. The sequence boundaries within the Pannonian formations also play an important role in trapping.

Accumulations in the area are primarily associated with the buried elevations of the basement rocks (KŐRÖSSY 2005a, SZABÓ et al. 2011, JÁMBOR 2012a–b), but hydrocarbons may occur in smaller folded structures and in hidden or lithologically closed traps. Beside the dominant single occurrences in the pseudoanticline structures, most of the subordinated hydrocarbon accumulations are related to lithologic and combined faulted structural–lithologic traps.

Reservoirs in the Pannonian sequence frequently are in various facies sandstones (tubidite lobe, turbidite channel fill, channel fill incised into delta slope) in stratigraphic traps combined with faults (pseudoanticlines, "rollover" anticlines, semi-structures leaning against a fault) (SZENTGYÖRGYINÉ et al. 2012c).

With the more common application of the 3D seismic measurements the trap types remaining hidden earlier may also be recognised. Such are the Lower Pannonian turbidite sandstones pinching out at the flanks of the morphological highs, the downfaulted coarse-grained clastic successions situated at the "foot" of structural elevations, and the Upper Pannonian channel sands and smaller sand lenses (SZABÓ et al. 2011).

Occasionally hidden stratigraphic and lithologic traps may occur, among others in the Lower Pannonian basal sandstones and fractured calcareous marls, the transgressive basal turbidites, in the fans of the prodeltas, in the sediments of turbidity currents slipped down on delta slopes, in delta slope sandstone-layers, in the fluvial sediments of upper and lower delta plains, in the sandstone fills of former river beds, and in the small folds of the delta plains (RUMPLER et al. 2003).

Hydrocarbon occurrences in the southern part of Nagykunság

Data characterising the discovered reservoirs (hydrocarbon composition, calorific value, etc.) basically are originated from the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ), in other cases the source is indicated.

Berettyóújfalu. This field was discovered by the Mol Hungarian Oil and Gas Plc through the Beru–1 well deepened in 2006. The well drilled such gas saturated layers in the lowest part of the Lower Pannonian Szolnok Formation consisting of clay bearing sandstone, which can be classified as unconventional "tight gas" based on their petrophysical properties and well test results (SZENTGYÖRGYINÉ et al. 2012b). Beside Pannonian unconventional gas reservoirs pre-Pannonian Miocene conventional gas accumulations and one unconventional reservoir also occur in the field.

The six pre-Pannonian Miocene conventional gas occurrences were accumulated in a depth around 4,600 m bsl (gas-water contact, or GWC). The combustible part of the gases is 77.4–97.1%, the methane is 69.1–76.3%, the carbon dioxide is maximum 22.4%, nitrogen is 0.2–2.9%. The calorific value of the gases is 29.9–39.6 MJ/m^3, the C_{5+} (hydrocarbon compounds with more than five carbon atoms) is 9.3–50.9 g/m^3.

The pre-Pannonian Miocene unconventional natural gas reservoir (Beru–M–I–F/146 Beru–III NHCH) is situated also at 4,600 m bsl (GWC). The combustible part is 91.0%, the methane (CH_4) is 74.9%, the proportion of carbon dioxide (CO_2) 8.8%, that of nitrogen (N_2) 0.2%, the C_{5+} 26.8 g/m^3. The calorific value of the gas is 39.4 MJ/m^3.

The six Lower Pannonian unconventional natural gas reservoirs are situated in a depth between 2,771 and 3,012 m bsl (GWC) in clay-bearing sandstone. The gases have a calorific value of 37.8 MJ/m^3, their combustible part is 84.4%, CH_4 62.2%, CO_2 content is 9.5%, N_2 content 7.1%, C_{5+} 45.8 g/m^3.

In some of the wells hydraulic fracturing was also carried out (KOVÁCS ZS., GYURICZA ed. 2013a). A detailed study was prepared on the potential contamination of underground waters and the risk of induced seismicity (NÁDOR et al. 2015). The study demonstrated that the chances of contamination migrating away from the fracturing range is very low, thanks to the depressive pressure space and the aquiferous zones inclined to closing and therefore close naturally after the fracturing operation. The outflow from the fractured Miocene formations is impeded by the clay-bearing layers of the Endrőd Marl Formation and the Algyő Formation. The created fissures close back almost immediately in the presence of clay minerals, and swelling clays due to water impact enhance this effect. The compressional stress field typical for the Pliocene and Quaternary (HORVÁTH, TARI 1999) also favours closure of the faults, even though periodical recent activity of certain faults cannot be excluded, either (LEMBERKOVICS et al. 2005, WINDHOFFER, BADA 2005). The substantial differences between the depth of the water bodies and the fracturing operations have additional limiting effects. According to the study the risk of the induced seismicity can be neglected since the several kilometres thick sedimentary succession is able to absorb significant amount of energy.

Biharnagybajom. This oil occurrence with gas cap was discovered by the Bi–1 well in 1946. It was accumulated in a depth of 1,000 m bsl (oil–water contact, that is the OWC), in a Neogene pseudoanticline, below unconformity surface, in a reservoir consisting of pre-Pannonian Miocene sandstone, conglomerate, limestone and tuff. The 800.0 kg/m^3 density oil and the natural gas with a combustible part of 77.0% and a calorific value of 29.7 MJ/m^3 were produced from the reservoir up to the end of 1984 when it was abandoned (VÖLGYI et al. 1985).

Dévaványa. The Hungarian National Oil and Gas Trust (OKGT) discovered this field in 1980 by the Déva–1 well. Reservoirs were accumulated linked to the Neogene pseudoanticline above the morphological high of the Variscan crystalline basement, in combined lithologic–structural, and lithologic–stratigraphic traps. The field consists of an undersaturated oil reservoir, and 18 natural gas reservoirs in Middle Miocene or Lower Pannonian reservoir rocks.

The undersaturated oil reservoir (M–III) can be found in pre-Pannonian Miocene conglomerate in a depth of 2,342 m bsl (OWC). The oil is paraffinic type with 794.9 kg/m^3 density. Its dissolved gas content is 185.5 m^3/m^3. The combustible part of the dissolved gas is 94.6%, CH_4 56.6%, N_2 content 5.4%, the calorific value is 56.4 MJ/m^3, the C_{5+} is 159.8 g/m^3.

The Middle Miocene natural gas reservoirs (Mioc–I, –II) are situated in a depth between 2,170.5 and 2,119 m bsl (GWC) in heterogeneous Badenian reservoir rocks, consisting of biogenic clastic limestone, fine-grained sand-bearing argillaceous marl, and carbonate cemented coarse-grained sandstone, occasionally with tuffaceous intercalations (SZENTGYÖRGYINÉ ed. 1989). The combustible part of the gases is 82.2 and 75.7%, their calorific value is 36.5 and 34.5 MJ/m^3. The CH_4 content is 65.5 and 62.2%, CO_2 0.2 and 3.6%, N_2 17.6 and 20.7%, the C_{5+} 25.8 and 55.8 g/m^3, condensate content is 78.5 and 55.8 g/m^3, respectively.

Most of the sixteen Lower Pannonian natural gas occurrences were accumulated between a depth of 1,960 and 2,261 m bsl (GWC), in higher position in the north-east, than in the SW, their lateral extensions are uncertain (SZENTGYÖRGYINÉ ed. 1989, BONER, VÖLGYI 1984, VÖLGYI et al. 1985). Reservoir rocks are the Szolnok Sandstone Formation and the Endrőd Marl Fm Vásárhely Marl Member. The calorific value of the gases is 33.1–40.0 MJ/m^3, combustible part is 82.8–93.8%, CH_4 5.1–89.7%, CO_2 maximum 6.0%, N_2 4.4–11.9%, C_{5+} 6.1–97.2 g/m^3, based on the data available from a part of the accumulations. Eight reservoirs in the field provide 27.9–131.6 g/m^3 condensate as well.

Dévaványa South (Dévaványa-Dél). This area was investigated already at the end of the 1980s. Later four natural gas reservoirs were discovered by the HHE-Déva–1–5 wells (Dévaványa–II area) drilled by HHE Hungarian Horizon Energy Ltd in the course of 2006–2007 at a depth of 2,501.5 and 2,909.5 m bsl (GWC). The reservoirs could be produced using conventional method. The gases were accumulated in Palaeozoic fractured metamorphic rocks and Lower Pannonian sandstone. The combustible part of the gases is between 87.8 and 95.3%, the calorific value 35.2–36.4 MJ/ m^3, CH_4 76.9–89.0%, CO_2 3.7–5.6%, N_2 1.0–6.6%, C_{5+} is 21.1–45.1 g/m^3.

Dévaványa East (Dévaványa-Kelet). Hungarian Horizon Energy Ltd drilled wells (HHE-Déva-K–1/B, –2 and –3) at the Dévaványa–III area in 2008, where five natural gas reservoirs were discovered in sandstone with tectonic closures. The combustible part of the gases is 91.0–95.8%, the composition: CH_4 88.9–91.0%, CO_2 2.9–4.2%, N_2 0.6–4.9%, C_{5+} 0.1–0.4 g/m^3. The calorific value varies between 32.0 and 36.0 MJ/m^3. The gas contains 9.1–21.0 g/m^3 condensate as well.

Endrőd North (Endrőd-Észak). This field was discovered in 1978 by the En-É–1 well, in which the OKGT (Hungarian National Oil and Gas Trust), later the Mol Hungarian Oil and Gas Plc identified 15 natural gas reservoirs, two commercial oil and two smaller oil reservoirs up to 1994 (PAP, NAGYNÉ 1997a). The commercial oils accumulated in Middle Miocene reservoir rocks, above the crystalline basement high complex which has complicated structure and diverse lithology. Substantial, 114% overpressure is dominated in the oil reservoirs (BONCZ et al. 1994, SZABÓ et al. 2011). The natural gas accumulated in combined structural–lithologic traps of the Neogene pseudoanticline, in Pannonian reservoir formations (VÖLGYI et al. 1985).

The lower undersaturated oil reservoir is found in Middle Miocene breccia derived from metamorphic rocks (M–br–8 at 2,815 m bsl OWC). The density of the paraffinic type oil is 826.0 kg/m^3, the dissolved gas content is 140 m^3/m^3, the combustible part of the gas is 66.0%, CH_4 45.8%, CO_2 1.5%, N_2 is 32.5% C_{5+} 47.6 g/m^3. The calorific value of the gas is 33.3 MJ/m^3. The amount of the condensate is significant on national scale, 4701.8 g/m^3.

The higher position undersaturated Miocene oil reservoir (M–mko–8) was accumulated in Badenian biogenic, lithothamnium limestone at a depth of 2,768 m bsl (OWC). This reservoir holds oil and dissolved natural gas of the same characteristics as the M–br–8 reservoir.

The Lower Pannonian oil accumulation is not of commercial-grade, it was trapped in calcareous marl (Tótkomlós Calcareous Marl Member) at a depth of 2,690 m bsl (OWC) (BONCZ et al. 1994, SZABÓ et al. 2011).

The twelve Lower Pannonian natural gas reservoirs are found in the lower part of the prodelta–delta slope sandstones at a depth between 1,854.5 and 2,373 m bsl (GWC). The combustible part of the natural gas is 93.0–96.6%, CH_4 84.1–94.3%, CO_2 2.2–5.3%, N_2 0.8–2.2%, C_{5+} 5.3–68.0 g/m^3. The calorific value is 35.1–39.4 MJ/m^3. One of the gas reservoirs also provides 77.3 g/m^3 condensate.

The gases of the three Upper Pannonian reservoirs were accumulated in delta plain sandstones at a depth of 908–1,230 m bsl (GWC). The combustible matter content of the natural gases is 98.4–98.9%, the calorific value is 35.3–35.5 MJ/m^3. The gases contain 98.2–98.7% CH_4, CO_2 content is maximum 0.22%, N_2 0.1–0.2%, in the middle reservoir C_{5+} is 0.64 g/m^3.

Endrőd–I. This natural gas field was discovered by the OKGT with the En–2 well in a Neogene pseudoanticline structure in 1971. Reservoirs are found in combined structural–lithologic traps in Lower and Upper Pannonian clay-bearing sandstones.

The fifteen Lower Pannonian reservoirs are situated at a depth of 1,867–2,098.5 m bsl (GWC). The combustible part of the gases is 90.0–98.0%, the CH_4 content reaches 85.5%, the proportion of CO_2 is maximum 6.0%, the N_2 is maximum 4.1%. The calorific value of the gases is 34.8–39.1 MJ/m^3.

The eight Upper Pannonian reservoirs were accumulated at a depth of 775–1,260 m bsl (GWC). Gases have 93.4–98.3% combustible part, CH_4 92.9–98.2%, CO_2 0.1–6.0%, N_2 0.4–0.6% (VÖLGYI et al. 1985).

Endrőd–III. The natural gas field was discovered by the OKGT in a Neogene pseudoanticline with NE–SW axial direction by the En–16 well drilled in 1976 (VÖLGYI et al. 1985). A total of 17 reservoirs were discovered until the mid-1980s. Later by further exploration additional accumulations were identified mainly in Lower Pannonian and partly in Upper Pannonian clay-bearing, and silty sandstone reservoirs.

Most of the twenty five Lower Pannonian reservoirs can be found at a depth between 1,886 and 2,182 m bsl (GWC). The combustible part of the gases is 91.1–96.5%, the calorific value is 34.7–39.8 MJ/m^3. The CH_4 content is mostly in a range of 82.1–95.0%, CO_2 is maximum 7.0%, N_2 is below 4.3%. In eight of the accumulations the amount of C_{5+} is 17.0–100.0 g/m^3.

The nine Upper Pannonian reservoirs are situated at a depth of 1,051–1,682 m bsl (GWC). Based on the available data the combustible part of the gases is 94.5–96.6%, the CH_4 is 84.0–92.4%, CO_2 maximum 2.2%, N_2 maximum 3.6%. The calorific value of the gases is 37.5–40.3 MJ/m^3. Six occurrences also provide 24.0–59.1 g/m^3 condensate.

Endrőd–III/C. OKGT discovered this field by the En–12 well in 1975. The field consists of four natural gas reservoirs, which accumulated in Pannonian sandstones, and silty sandstones.

The three Lower Pannonian natural gas reservoirs can be found at a depth between 1,990 and 2,450 m bsl (GWC) in a combined structural–stratigraphic trap. The combustible matter content is 59.7–95.7%, the calorific value is 23.5–35.8 MJ/m^3. The CH_4 content in the gases is 59.4–94.9%, CO_2 1.9–38.4%, N_2 0.5–2.2%, the C_{5+} 2.8–37.3 is g/m^3. The gas of the lower and in particular of the upper reservoir is of better quality than that from the middle one. The lower reservoir provides also 15.1 g/m^3 condensate.

The Upper Pannonian gas reservoir is found at a depth of 1,283 m bsl (GWC) in a trap closed by facies change. The combustible part of the natural gas is 96.2%, CH_4 95.8%, CO_2 1.9%, N_2 1.9%, C_{5+} 0.71 g/m^3.

Endrőd East (Endrőd-Kelet). Hungarian Horizon Energy Ltd discovered a natural gas occurrence (Bomber reservoir) here in 2008 by the HHE-Endrőd–1 well. The gas which was accumulated in sandstone reservoir holds 93.6% combustible part, CH_4 83.9%, CO_2 3.7%, N_2 2.7%. The calorific value of the gas is 36.5 MJ/m^3, and it has 21.5 g/m^3 condensate.

Földes East (Földes-Kelet). This natural gas field was discovered by the OKGT with the Föl–2 well in 1983 on the SW–NE direction series of blocks around Földes, to the south of a strike-slip zone, on semi-structures leaning against a main tectonic line. Reservoirs are held by Middle Miocene and Lower Pannonian formations, and they have fault closing (Szentgyörgyiné et al. 2002).

The two pre-Pannonian Miocene reservoirs lie at a depth of 3,215.5 and 3,195 m bsl (GWC). The lower reservoir is situated in clay-bearing sandstone, the upper one is in tuffaceous sandstone. The combustible part of the gases is 38.1 and 72.1%, CH_4 37.2 and 64.5%, CO_2 61.0 and 25.8%, N_2 0.9 and 2.1%, C_{5+} in the lower reservoir 0.6 g/m^3. The calorific value is 13.9 and 27.8 MJ/m^3. The upper accumulation is of better quality than the lower one, and has 36.7 g/m^3 condensate as well.

Mol Hungarian Oil and Gas Company Plc discovered further two natural gas reservoirs by the Föl-NE–1 well drilled in 2007 in pre-Pannonian Miocene tuff, tuffite, and tuffaceous sandstone succession at a depth of 3,253.5 and 3,320 m. Reservoirs are situated to the south (M–2 reservoir) and N–NE (M–14 reservoir) from the west–east direction fault crossing the Földes East structure on a semi-structure leaning against a fault of NE–SW strike, in an anticline structure. Beside the thick impermeable Miocene marl and tuff-stripped argillaceous marl, tectonics also plays an important role in the closing of the traps. The faults have low permeability between the reservoirs, and no active water flow can be reckoned with. The composition of the gases is different in the two reservoirs, in the M–14 the calorific value is 14 MJ/m^3, the combustible part of the natural gas is 38.1% (Szentgyörgyiné et al. 2012b).

Six Lower Pannonian natural gas reservoirs are located in delta slope and shelf-break clay-bearing sandstones between a depth of 1,546 and 2,580 m bsl (GWC). Natural gases contain 89.8–97.1% combustible matter with 72.2–88.8% CH_4, 0.7–6.2% CO_2 and 1.3–4.0% N_2, 11.3–155.8 g/m^3 C_{5+}. Their calorific value is 38.1–44.9 MJ/m^3 (Szentgyörgyiné et al. 2012b, Tormássy, Szilágyi 2000).

Földes West (Földes-Nyugat). It was discovered by the OKGT with the Föl–1 well in 1982. The field consists of oil and natural gas reservoirs lying on a SW–NE direction series of blocks. Hydrocarbons accumulated in Middle Miocene, and Lower Pannonian formations.

The pre-Pannonian Miocene undersaturated oil reservoirs (M–6 and M–11 reservoirs) are found at a depth of 1,900 and 2,727.5 m bsl (OWC) in Miocene conglomerate, breccia, and tuffaceous sandstone. Density of the paraffinic type oils are 788.1 and 823.0 kg/m^3. The quantity of the dissolved gas is 50 and 260 m^3/m^3, the combustible part is 96.2 and 92.9%, CH_4 81.3 and 82.0%, CO_2 0.7 and 0.1%, N_2 3.1 and 7.0%, C_{5+} 78.7 and 25.6 g/m^3. The calorific value of the gas is 42.5 and 38.6 MJ/m^3. The Lower Pannonian oil reservoir is situated in calcareous marl at a depth of 2,424 m bsl (OWC). The paraffinic–intermediate type oil is of 804.7 kg/m^3 density. The dissolved gas is 50 m^3/m^3, the calorific value is 42.0 MJ/m^3.

The Middle Miocene natural gas occurrences (M1 and M3) were accumulated in Sarmatian and Badenian sandstone, as well as in tuffaceous sandstones (Tormássy, Szilágyi 2000). Gases contain 98.2 and 91.3% combustible matter, respectively, with an overwhelming part made up of CH_4, CO_2 maximum 0.7%, N_2 1.1 and 8.0%, the amount of C_{5+} is 39.2 and 11.0 g/m^3. The calorific value of the gases is 40.0 and 35.7 MJ/m^3. The deeper position accumulation is of the better quality.

Füzesgyarmat. OKGT discovered this field in 1974 with the Fü–3 well on the Füzesgyarmat high. Three oil reservoirs and two carbon dioxide gas reservoirs are here in pre-Pannonian Miocene sandstones, clay-bearing and tuffaceous sandstones, and in limestone.

Oil reservoirs are situated at a depth between 1,753.5 and 1,768.5 m bsl (OWC) and overpressure of 16–67% is observed

in them (SZENTGYÖRGYINÉ et al. 1997a, SZABÓ et al. 2011). The oil is paraffinic with 885.8–916.3 kg/m^3 density, and 0.06% sulphur content is also present. The gases consist of 91.7–96.8% CO_2, the combustible matter content is merely 2.1–6.0%, CH_4 2.0–5.2%, N_2 is 1.1–2.3%, C_{5+} 5.7–63.0 g/m^3 (SZENTGYÖRGYINÉ et al. 1997a).

The two carbon dioxide natural gas reservoirs can be found approximately at a depth of 1,753.5 m bsl (GWC). The combustible part of the gases is merely 7.1 and 2.9%.

Hajdúbagos East (Hajdúbagos-Kelet). OKGT discovered the natural gas field by the Hbag-K–1 well drilled in 2011, found predominantly in Upper Pannonian, and subordinately in Lower Pannonian sandstones. The 17 reservoirs of the field are in fault closed traps, two reservoirs were situated in stratigraphic traps.

The natural gas in the Lower Pannonian reservoir has 95.9% combustible matter, the calorific value of it is 33.9 MJ/m^3. The CH_4 ratio is 93.1%, CO_2 4.0%, N_2 0.1%, the C_{5+} 8.5 g/m^3.

The eighteen Upper Pannonian natural gas reservoirs are located at a depth between 1,842.5 and 2,218.2 m bsl (GWC). The combustible part of the gases is 96.0–97.6%, CH_4 89.5–93.1%, CO_2 2.2–4.0%, N_2 maximum 0.2%, C_{5+} 5.5–15.7 g/m^3. Each of the reservoirs provides condensate as well in an amount of 20.3–42.8 g/m^3.

Hosszúpályi South (Hosszúpályi-Dél). This natural gas field was discovered by Mol Plc with the Hpi-D–1 well which was drilled in 2001, found in mainly Upper Pannonian, and partly Lower Pannonian reservoir rocks (SZENTGYÖRGYINÉ et al. 2002, 2003). Reservoirs are situated in combined structural–stratigraphic traps (SZENTGYÖRGYINÉ et al. 2003, 2005). The field consists of two hydrodynamically isolated parts.

Lower Pannonian reservoirs are situated at a depth of 1,992.5–2,070 m bsl (GWC), gases have 96.1–97.3% combustible part, CH_4 88.4–89.5%, CO_2 2.6–3.5%, N_2 maximum 0.5% C_{5+} 19.1–45.8 g/m^3. Condensate can be extracted from two of the accumulations in an amount of 43.3 and 52.2 g/m^3, respectively.

The twenty reservoirs of the Upper Pannonian natural gases are delta front – delta plain sandstones, clay-bearing and silty sandstones of meandering river channel. These reservoirs can be found at a depth of 1,298–1,872 m bsl (GWC). Gases have 96.8–98.3% combustible part, the CH_4 is 89.3–91.4%, CO_2 1.1–2.8%, the N_2 is maximum 2.0%, C_{5+} 17.9–59.6 g/m^3, the calorific value is 37.7–40.3 MJ/m^3. Fourteen of the reservoirs provide condensate in an amount of 36.5–45.4 g/m^3 as well.

Kaba South (Kaba-Dél). It was discovered by the OKGT Kab-D–2 well in 1978. The undersaturated oil occurrence is situated at a depth of 1,996 m bsl (OWC), the oil was accumulated in a stratigraphic trap formed under the unconformity surface of the Neogene pseudoanticline overlying the basement elevation. Its reservoir is fractured gneiss and pre-Pannonian Miocene conglomerate–sandstone, and breccia (VÖLGYI et al. 1985). The oil is paraffinic–intermediate type, with 854.5 kg/m^3 density, and 0.3% sulphur content. The dissolved gas is 151 m^3/m^3, the combustible part is 89.7%, with a calorific value of 43.4 MJ/m^3. The CH_4 in the gas is 68.5%, CO_2 4.7%, N_2 5.6%, the C_{5+} is 42.0 g/m^3.

Körösladány. OKGT discovered the field by the Köl–1 well drilled in 1981. One oil and one natural gas reservoir is known here in basement metamorphic rocks and in Middle Miocene sediments.

The natural gas reservoir in the basement rocks is situated at a depth of 2,790 m bsl (GWC) in fractured metamorphites, in structural trap. The folded metamorphic reservoir rocks consist of amphibolite and biotite gneiss intersected to blocks with normal and reverse faults and joints. The western boundary of the reservoir is an impermeable barrier caused by reverse fault (SZENTGYÖRGYINÉ et al. 1997b). The natural gas contains 90.3% combustible part, the CH_4 is 65.4%, CO_2 0.4%, N_2 9.3%, C_{5+} 154.3 g/m^3. The calorific value of the gas is 48.0 MJ/m^3.

Undersaturated oil was accumulated at a depth of 2,646.5 m bsl (OWC) in small closed structure formed in pre-Pannonian Miocene biogenic limestone. Miocene limestone has unfavourable reservoir properties; therefore acidisation techniques took place in several instances. The oil is paraffinic; its density is 803.0 kg/m^3. The dissolved gas is 450 m^3/m^3, the combustible part of the gas is 54.8%, CH_4 41.9%, CO_2 41.9%, N_2 3.3%, C_{5+} 47.7g/m^3. The calorific value of the dissolved gas is 21.4 MJ/m^3, and it provides 618.0 g/m^3 condensate as well.

In the Köl–3 well the Lower Pannonian calcareous marl was also productive, in which natural gas and intermediate condensate were both observed.

Köröstarcsa. OKGT drilled the Köt–I well in 1976–77 and discovered a natural gas field on a smaller local elevation which is separated from the Gyoma–Dévaványa buried ridge by a large tectonic line. The ages of the reservoir rocks are Mesozoic and Middle Miocene, high temperature and overpressure occur above the unconformity zone of the metamorphic and Mesozoic rocks (SZENTGYÖRGYINÉ et al. 1997b, 2012d; SZABÓ et al. 2011). The great depth, the unfavourable gas composition and the complicated tectonic set up of the field impeded the exploration (KŐRÖSSY 2005b, NAGYNÉ et al. 1993).

The four Mesozoic and Mesozoic – Middle Miocene natural gas reservoirs can be found in a depth between 3,154 and 3,255.5 m bsl (GWC) mainly in Lower Triassic quartz sandstone, partly in limestone, dolomite, dolomite breccia and pre-Pannonian Miocene miscellaneous reservoirs. Gases contain 53.0–55.0% combustible part, the CH_4 is 46.3–48.4%, CO_2 29.4–31.2%, N_2 14.5–15.6%, their calorific value is 22.9–23.5 MJ/m^3. Two reservoirs provide 307.2 and 566.8 g/m^3 condensate as well, respectively.

The three Middle Miocene natural gas reservoirs were formed in Badenian lithothamnium limestone at a depth of 3,169.5–3,208.5 m bsl (GWC). The combustible matter content of the gases is 9.6–49.4%, CH_4 9.5–44.19%, CO_2 36.6–

85.7%, N_2 4.6–13.9%, C_{5+} maximum 25.1 g/m^3, their calorific value is 3.5–19.9 MJ/m^3. Two accumulations also hold condensate in an amount of 106.4 and 118.3 g/m^3.

Kunszentmárton. A natural gas occurrence was discovered by the OKGT in Lower Pannonian sandstone of the Kunszt–1 well in 1979 at a depth of 2,084.5 m bsl (GWC), which is closed by lithological changes. The combustible part of the gas is 92.5%, CH_4 90.9%, CO_2 1.8%, N_2 5.7%, C_{5+} 2.9 g/m^3. The calorific value of the gas is 34.0 MJ/m^3.

Martfű South (Martfű-Dél). This hydrocarbon field was discovered by the Mar–3 well of the OKGT in 1981, which consists of an oil and seven natural gas reservoirs. Hydrocarbons were accumulated in Lower Cretaceous, pre-Pannonian Miocene and Lower Pannonian formations.

The oil reservoir with gas cap can be found in a depth of 1,987 m bsl (OWC) in Lower Cretaceous diabase agglomerate, pre-Pannonian Miocene sandstone, and conglomerate. The oil is paraffinic, its density is 829.3 kg/m^3, and 0.19% sulphur is also contained therein. The dissolved gas content is 121.3 m^3/m^3, the combustible part of the dissolved gas is 94.7%, CH_4 75.7%, CO_2 4.7%, N_2 1.6%, C_{5+} 242.5 g/m^3. The calorific value of the gas is 40.8 MJ/m^3.

The Mesozoic–Miocene natural gas reservoir is at a depth of 1,916 m bsl (GWC) also in Lower Cretaceous diabase agglomerate, as well as in pre-Pannonian Miocene sandstone and conglomerate. The combustible matter content of the gas is 94.0%, the calorific value is 41.0 MJ/m^3.

The six Lower Pannonian natural gas reservoirs are located in a depth between 1,565.5 and 1,854 m bsl (GWC) in basal calcareous marl and sandstones. The combustible part of the gases is 81.1–95%, CH_4 69.0–84.5%, CO_2 2.7–14.4%, N_2 1.7–5.5%, C_{5+} 40.7–242.2 g/m^3, their calorific value is 35.6–48.6 MJ/m^3. The natural gas reservoir at a depth of 1,777.5 m bsl (GWC) provides 697.6 g/m^3 condensate as well.

Martfű North II (Martfű-Észak–II). Two natural gas reservoirs were discovered by the OKGT in 1982 with the Mar–16 well in Lower Pannonian clay-bearing sandstone, at a depth of 1,647.5 and 1,685 m (GWC) (Völgyi et al. 1985). They are closed tectonically. The 89.7–92.2% combustible matter content gases have a calorific value of 43.9–45.5 MJ/m^3. Gases contain 68.0 and 72.5% CH_4, 7.0 and 3.4% CO_2, as well as 3.3 and 4.4% N_2, respectively. 220.2–236.1 g/m^3 condensate can also be extracted from them.

Mezőtúr. This natural gas reservoir was discovered by the OKGT with the Mtúr–1 well which was drilled in 1981 above a basement high of northern–southern strike sinking towards the south, surrounded by deep basins from the west, east and south. The natural gas was accumulated in a pinched out Lower Pannonian prodelta sandstone reservoir at a depth of 2,173 m bsl (GWC) (Gajdos et al. 1997b, Szabó et al. 2011). The combustible part of the natural gas is 95.0%, CH_4 86.5%, CO_2 3.9%, N_2 1.1%, C_{5+} 79.5 g/m^3 and hydrogen sulphide also appears in it. The calorific value of the gas is 40.2 MJ/m^3, and it also provides 65.3 g/m^3 paraffinic condensate as well.

Monostorpályi South-east (Monostorpályi-Délkelet). It was discovered by the Mol Plc with the Mpi-DK–1 well drilled in 1999. Two natural gas occurrences are found here with tectonic closing, they were accumulated in Upper Pannonian sandstone reservoir, at a depth of 1,916 and 1,987 m bsl (GWC). The combustible part of the gases is 97.3–97.4%, in which the CH_4 is 86.1–86.2%, CO_2 2.3%, N_2 0.4%, C_{5+} 43.5 and 47.1 g/m^3. The calorific value of the gases is 40.7–40.8 MJ/m^3.

Monostorpályi East (Monostorpályi-Kelet). Mol Plc discovered one natural gas reservoir in Upper Pannonian formations at a depth of 1,428 m bsl (GWC) by the Mpi-K–2 well completed in 2011. The natural gas has a calorific value of 38.1 MJ/m^3, the combustible part is 98.2%, CH_4 88.5%, CO_2 1.0%, N_2 0.8% and the C_{5+} 32.3 g/m^3.

Öcsöd. This natural gas reservoir was discovered by RAG Hungary Central Ltd by the RAG-Öcs–1 well completed in 2011, at a depth of 2,370 m bsl (GWC). The combustible part of the gas in the sandstone reservoir has 93.3%, the CH_4 is 73.6%, CO_2 4.8%, N_2 1.9%, C_{5+} 78.6 g/m^3. The calorific value of the gas is 41.5 MJ/m^3.

Örménykút. The OKGT discovered a carbon dioxide natural gas accumulation by the Örm–I well drilled in 1985, at a depth of 4,058.5 m bsl (GWC) in the Mesozoic basement, in Middle Triassic carbonate reservoir rocks. A minimal amount of combustible gas inflow was also observed from the Lower Pannonian silty sandstone-stripped argillaceous marl of the well. Beside the 92.6% CO_2 the carbon dioxide reservoir has merely 6.5% combustible part, CH_4 6.4%, N_2 0.9%, therefore the calorific value is only 2.3 MJ/m^3 (Szentgyörgyiné et al. 2012d).

Sáránd. A reservoir of a natural gas with low combustible part was discovered by the OKGT Hungarian National Oil and Gas Trust in 1983 with the Sáránd–I geological–geophysical exploration well, in Lower Pannonian rocks, on the strongly tectonised western flank of the Derecske Trough, along the faults connected to the main strike-slip zone. The gas was accumulated at a depth of 1,893 m (GWC) in the upper part of the Algyő Formation in a shelf-break zone, in fine-grained sandstone of a lithologic trap. The sandstone reservoir rock becomes argillaceous in all directions and leans against a fault. The 97.7% combustible part containing natural gas has a calorific value of 55.4 MJ/m^3, CH_4 72.1%, CO_2 2.3%, N_2 0.04%, C_{5+} 336.6 g/m^3 (Szentgyörgyiné et al. 2012b, Tormássy, Szilágyi 2000).

Sáránd shallow (Sáránd-sekély). This field which consists of two natural gas accumulations, was discovered by the OKGT along the faults attached to the main strike-slip zone crossing the Derecske Trough, in a strongly tectonised area, in a pseudoanticline structure, with the Sáránd-S–1 well in 1986. The reservoirs are set up by Upper Pannonian formations, the nearshore delta sediments of the Újfalu Sandstone Formation. Within these the reservoir rocks are the uppermost member of the delta front facies sandstone succession and the river channel facies sequence consisting of alternating fine-grained

sandstone and silt. Both natural gas reservoirs can be found in the block of a flower structure dropped into the deepest position and tilted from its place. They are situated at a depth of 1,740 and 2,046 m (GWC). Gases contain 96.7 and 97.5% combustible part, the CH_4 is 88.0 and 91.5%, CO_2 1.6 and 3.2%, N_2 0.9 and 0.1%, C_{5+} 78.1 and 68.5 g/m^3, respectively. The calorific value of the gases is 38.5 and 41.0 MJ/m^3 (TORMÁSSY, SZILÁGYI 2000; SZENTGYÖRGYINÉ et al. 2003, 2012b).

Szarvas. This natural gas field was discovered by the OKGT in 1961 by the Szr–1 well mainly in Lower Pannonian, and partly in Upper Pannonian sandstone reservoir rocks. The typical geophysical well logs of the Szarvas Szr–6 well in the field can be seen on Figure 4.6.9.

The nine Lower Pannonian reservoirs are situated at a depth between 2,307.5 and 2,330 m bsl (GWC). The quality of the gases varies in a wide range. The combustible part of them is 3.0–91.6%, CH_4 3.1–80.4%, CO_2 8.1–96.7%, N_2 0.3–3.2%, C_{5+} maximum 66.6 g/m^3. Three reservoirs have condensate as well in an amount of 93.5–143.3.

The three Upper Pannonian reservoirs can be found at a depth 2,307–2,446.5 m bsl (GWC). The combustible part is

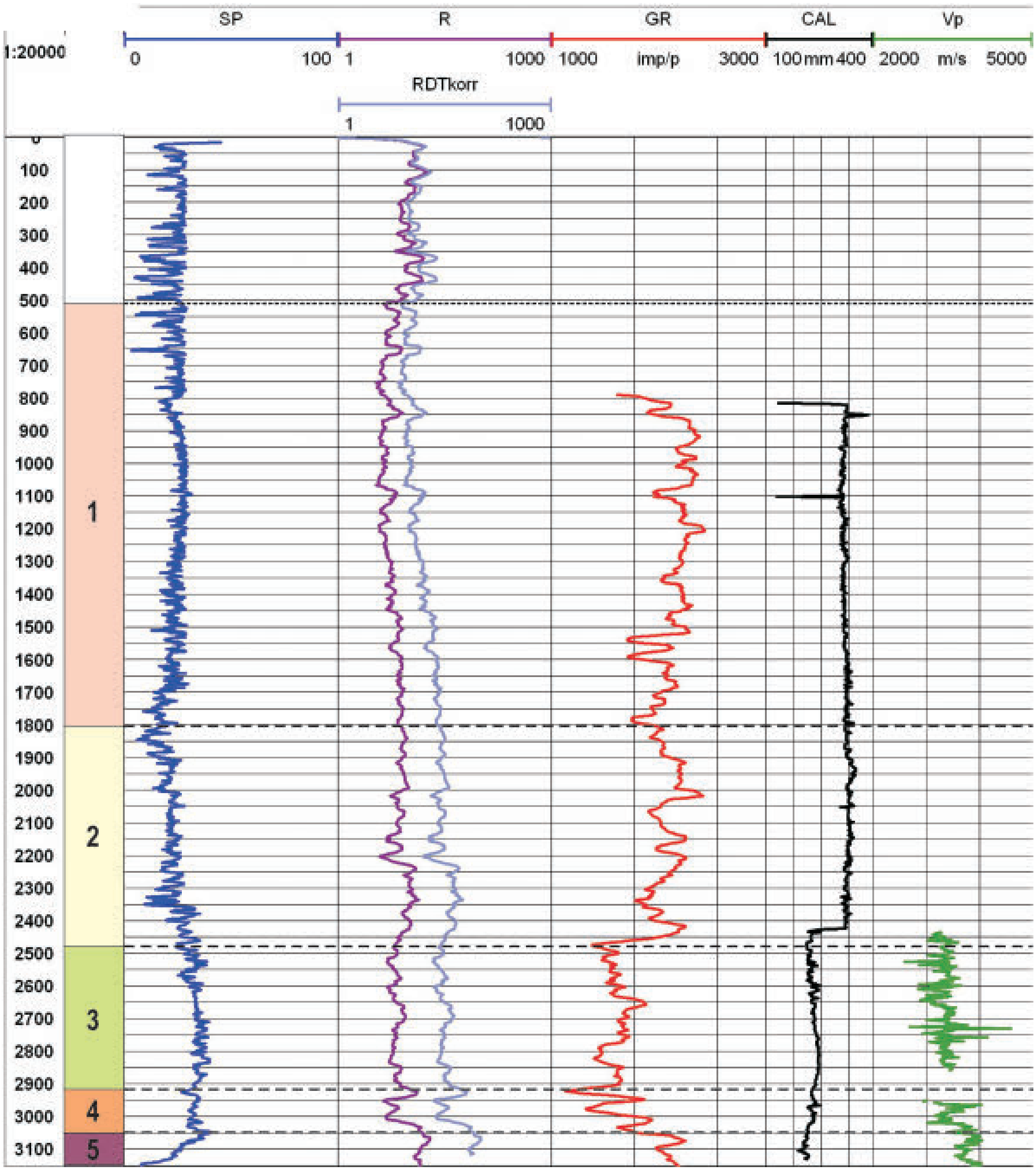


Figure 4.6.9. Geophysical well logs of the Szarvas Szr-6 well

Legend: SP: spontaneous potential, R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log; Vp: acoustic velocity profile. *Geological column:* 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Szolnok Fm and. Endrőd Fm (Lower Pannonian), 5. Pre-Pannonian Miocene, 6. Variscan basement

71.6–84.9%, CH_4 64.5–76.5%, CO_2 13.2–26.8%, N_2 1.7–2.5%, C_{5+} 25.0–86.7 g/m^3. The condensate content is 67.2–115.2 g/m^3.

Szeghalom. The OKGT Hungarian National Oil and Gas Trust discovered this field in 1980 by the Sz–2 well, reservoirs of which are situated in the basement elevation, and the overlying Neogene pseudoanticline, in combined structural–stratigraphic traps, and in lithologic traps formed under unconformity surface. The field consists of two oil and two natural gas accumulations.

The oil reservoirs can be found in a depth between 2,014 and 1,995 m (OWC) in fractured metamorphites, mainly in gneiss and amphibolite (Szeghalom–1 reservoir), as well as in Middle Miocene sandstone, conglomerate, and breccia reservoirs (Szeghalom–1, –2). The two oil reservoirs are connected hydrodynamically, and are overpressured. The density of the paraffinic oil is 806.9 and 803.2 kg/m^3. The combustible part of the dissolved gases is 95.4 and 93.0%, CH_4 81.2 and 76.1%, CO_2 0.2 and 0.4%, N_2 5.4 and 6.6%, C_{5+} in the gas of the oil which is in metamorphites 57.8 g/m^3. The calorific value of the gases is 41.1 and 44.1 MJ/m^3.

The two natural gas reservoirs are situated in Lower Pannonian sandstones at a depth of 1,767 and 1,533.5 m (GWC). The combustible part is 97.9 and 93.1%, CH_4 87.2 and 80.7%, CO_2 1.3 and 0.9%, N_2 5.6 and 1.2%, C_{5+} 52.8 and 74.4 g/m^3. The calorific value is 40.6 and 41.0 MJ/m^3 (Gajdos et al. 1985a).

Szeghalom North–1 (Szeghalom-Észak–1). This field in the basement rocks and Middle Miocene formations were discovered in 1982 by the Sz-É–1 well (Szentgyörgyiné et al. 1997a).

The oil reservoir of the basement can be found at a depth of 1,859.5 m bsl (OWC) in metamorphic basement rocks, in cataclastic, mylonitic biotite gneiss and tectonic breccia containing amphibolite bodies as well. The closing is partly provided by thick impermeable metamorphic rocks. The density of the paraffinic oil is 805.7 kg/m^3. The combustible part of the gas is 89.3%, the calorific value 45.4 MJ/m^3, CH_4 66.5%, CO_2 1.2%, N_2 9.5%, C_{5+} 111.4 g/m^3 (Szentgyörgyiné et al. 1997a, 2012b; Tormássy, Szilágyi 2000).

The Miocene reservoir (SZE–M–I.–CO_2) is situated at a depth of 1,715 m bsl (OWC) in pre-Pannonian Miocene conglomerate and biogenic limestone. The natural gas consists mainly of 97.1% CO_2, the proportion of the combustible part is only 1.8% (Szentgyörgyiné et al. 1997a, 2012b; Tormássy, Szilágyi 2000).

Szeghalom North-5 (Szeghalom-Észak–5). It was discovered by the OKGT by the Sz-É–5 well in 1985. The field consists of one oil reservoir with gas cap and one natural gas reservoir in basement metamorphic and Middle Miocene reservoir rocks.

The basement natural gas reservoir (Pt–II) can be found in a depth of 2,204 m bsl (GWC) in fractured metamorphites, mainly in gneiss and amphibolite. The gas contains 95.6% combustible components, the CH_4 is 78.4%, the CO_2 content 3.6%, the proportion of N_2 0.8%, C_{5+} 48.3 g/m^3. The calorific value of the gas is 45.3 MJ/m^3 (Szentgyörgyiné et al. 1997a, 2012b; Tormássy, Szilágyi 2000).

The oil with gas cap (M–II) at 2,225 m bsl (OWC) was accumulated in pre-Pannonian Miocene conglomerate. The intermediate oil has 799.0 kg/m^3 density. The dissolved gas contains 94.3% combustible part, the CH_4 is 70.9%, CO_2 0.2%, N_2 5.5%, C_{5+} 111.4 g/m^3. The calorific value of the gas is 44.5 MJ/m^3, the condensate content is 290.3 g/m^3.

Szeghalom West (Szeghalom-Nyugat). The OKGT Hungarian National Oil and Gas Trust discovered this small oil reservoir with gas cap by the Sz-Ny–1 well in 1989, which accumulated in the western edge of the Derecske Trough. The reservoir found at a depth of 2,202.5 m bsl (OWC) is Middle Miocene (Badenian) coarse-grained sandstone and conglomerate derived from metamorphites. The density of the paraffinic–intermediate oil is 830 kg/m^3, and contains 0.22% sulphur as well. The combustible part of the natural gas is 95.0%, CH_4 82.9%, CO_2 0.1%, N_2 is 4.9%, C_{5+} 34.9 g/m^3. The calorific value of the gas is 39.8 MJ/m^3.

Túrkeve South (Túrkeve-Dél). HHE Hungarian Horizon Energy Ltd discovered a natural gas reservoir (Kinglet) at a depth below 2,315 m by the HHE-Túrkeve-Dél–1 well drilled in 2008. The reservoir rock is carbonate cemented sandstone of the Lower Pannonian Szolnok Formation which is intersected by clay beds and sandstone strips. The combustible part of the gas is 94.8%, CH_4 83.0%, CO_2 3.3%, N_2 1.9%, C_{5+} 47.9 g/m^3, the condensate content 48.0 g/m^3. The calorific value of the gas is 38.8 MJ/m^3.

Túrkeve North-east (Túrkeve-Északkelet). Hungarian Horizon Energy Ltd discovered three natural gas reservoirs (Knoya–0, –1, –3) in 2008 with the HHE-Túrkeve-Kelet–1 well in the prodelta clay-bearing silty sand succession of the Lower Pannonian Szolnok Sandstone Formation, at a depth between 1,714 and 1,830 m. The occurrences were accumulated in structural traps with fault closure. Gases contain 87.2–96.9% combustible part, the CH_4 is 81.6–85.0%, the proportion of CO_2 is 1.6–1.9%, the N_2 is 1.5–10.9%, the C_{5+} is 23.9–48.4 g/m^3. The calorific value of the natural gases is 33.0–39.2 MJ/m^3. Two reservoirs provide 48.4 and 23.9 g/m^3 condensate.

Túrkeve North-west (Túrkeve-Északnyugat). Several wells of the HHE Hungarian Horizon Energy Ltd were successful in this area. The gas reservoirs of the HHE-Túrkeve-Nyugat–5 well (Hidden reservoir), and the HHE-Túrkeve-Nyugat–13 well (Hidden West reservoir) are found in clay-bearing silty sandstone of the upper part of the Szolnok Sandstone Formation. The occurrence discovered by the HHE-Túrkeve-Nyugat–7 well (North Suicide reservoir) was accumulated in the lowest sandstone beds of the Szolnok Sandstone Formation, in the top of a structural high. The accumulated gases are dry gas and mixed gas.

Túrkeve East (Túrkeve-Kelet). This field was discovered by the Te–3 well in 1962 in Lower and Upper Pannonian silty sandstone. A few of the accumulations can be found in tectonically closed traps. The Lower Pannonian undersaturated oil reservoir was situated at a depth of 1,925 m bsl (OWC) in sandstone and silty sandstone succession of the Szolnok Sandstone Formation. The density of the paraffinic–intermediate oil is 905 kg/m^3, the sulphur content is 0.2%, the amount of the dissolved gas in it is 50 m^3/m^3, the calorific value is 48.0 MJ/m^3. The combustible part of the gas is 94.0% with 72.6% CH_4, 0.03% CO_2 and 6% N_2, and 125.0 g/m^3 C_{5+} content (Szentgyörgyiné et al. 1993a, Pap, Nagyné 1997b–c).

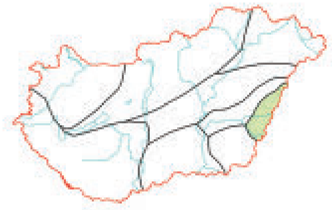
The eight Lower Pannonian natural gas reservoirs are also accumulated in silty sandstones of the Szolnok Sandstone Formation at a depth between 1,506 and 1,912 m bsl (GWC). The combustible part is 83.5–95.5%, CH_4 81.1–93.1%, CO_2 0.9–2.5%, N_2 3.6–14.0%, the C_{5+} content is 1.9–30.2 g/m^3. The calorific value of the gases is 31.3–34.5 MJ/m^3. One of the Lower Pannonian accumulations (GWC: 1,720 m bsl) provides 27.4 g/m^3 condensate as well.

The eight Upper Pannonian natural gas reservoirs were accumulated at a depth of 817.5–1,088 m bsl (GWC) in silty sandstone. The combustible matter in the gases is 94.1–99.7%, CH_4 90.9–98.6%, CO_2 content maximum 0.3%, N_2 content maximum 5.6%, the C_{5+} in one gas occurrence is 0.75 g/m^3. The calorific value of the gases is 33.8–37.1 MJ/m^3. The quality of gases in the Upper Pannonian reservoirs is somewhat better than in the Lower Pannonian reservoirs.

The overwhelming majority (90%) of the hydrocarbon occurrences known in the southern part of the Nagykunság area contain natural gas, the remaining being mainly undersaturated oil accumulations. Further hydrocarbon exploration of this area, first of all, by 3D seismic investigation of the hidden traps, will most probably lead to the discovery of new conventional and unconventional gas fields and oil reservoirs.

Hydrocarbon exploration areas in Hungary — Bihar

Ildikó Selmeczi



4.7

Exploration history

Possibilities of the hydrocarbon exploration in the south-eastern part of the Great Hungarian Plain was first dealt by Lajos Lóczy Jr., who has also written a study for the Hungarian–German Mineral Oil Company (MANÁT) (Lóczy Jr. 1934, 1941). Exploration in the Bihar area started already in the beginning of the 1940s; the Eötvös torsion balance measurements were started by the Eötvös Loránd Geophysical Institute and on assignment from MANÁT the Seismos and Prakla Company carried out gravity and seismic tests (Kőrössy 2005b). The geophysical measurements detected structures which were promising in terms of the hydrocarbon exploration in the Körösszegapáti–Biharkeresztes, Komádi, Álmosd, Kismarja as well as in the Furta and Zsáka areas.

The drilling exploration started at Körösszegapáti in 1943; up to 1950 16 wells were drilled (Kőrössy 2005b). As part of a renewed interest the NE part of the Bihar area was explored in 1980 (Bike–1 well) (Völgyi et al. 1985). Following the gravity measurements of MANÁT in the Komádi area the Eötvös Loránd Geophysical Institute carried out gravity and geomagnetic measurements in the 1960s. Based on the residual anomaly calculations a closed structure was evinced to the SW of Komádi settlement, which has been examined using seismic measurements as well. It has demonstrated that it corresponds to an elevation of the crystalline basement, and the Mesozoic succession was pinched out on the crystalline basement complex elevation. The exploration well (drilled by the OKGT National Oil and Gas Trust) was started in 1974 in the area, and the field was discovered by the Kom–1 well in the same year. Even though this particular wildcat was not productive, in the subsequent period further exploration and appraisal drilling activities were started. Reservoirs containing natural gas of favourable composition, some condensate and occasionally some oil have become known. In the surrounding of Komádi OKGT followed the exploration operations in 1976, and the delineation of the Komádi North field area was also completed in 1989. MOL Plc finished with the exploration of the Komádi–Mezősas area and the surroundings in 1999, and drilled exploration wells also in the Darvas–Komádi area between 1999 and 2010 (Kőrössy 2005b, Völgyi et al. 1985, Lawson et al. 1989, Szentgyörgyiné et al. 1997a, 1999a, 2010).

It has become known already through the first detailed gravity measurements of the 1940s, that the pre-Cenozoic basement is shallowing in the Kismarja area from a depth of 2,000 m up to a depth of approximately 900 m. The closed maximum showed a constant subsidence towards the Derecske Trough, and a slow ascent in the direction of the Réz Mountains (Munții Plopi) to the east. Decades later state-of-the-art seismic measurements demonstrated that the basement high is divided by faults. Drilling exploration was started already in 1944–45 by MANÁT. The Kism–1 and –2 wells — deepened on the northern and western sides of the basement high — were not productive. As a result of restarted exploration at the end of the 1970s, however, oil, combustible gas and CO_2 gas reservoirs became known in three separate fields (Kismarja, Kismarja West and Kismarja South) (Kőrössy 1991, Szentgyörgyiné et al. 1999b).

The gravity measurements in the Álmosd area at the beginning of the 1940s (Bassó 1944) indicated that the observed maximum was on the other side of the national boundary. This was confirmed by seismic measurements after 1975. Drilling exploration started in 1977, and the oil and natural gas field (Álmosd Álm–2 well) was discovered by the same year (Völgyi et al. 1985, Kőrössy 1991).

Furta natural gas field has become known in 1957 (Fu–1 well). The Fu–2 and –3 dry wells were deepened in 1958, and the drilling exploration was restarted in 1976–77 by drilling of further wells, several of which could be completed to produce gas (Kőrössy 1991, Sőreg et al. 1991). The Furta-Észak–1 well (1996) was drilled in order to explore the block of the northern part of the area, where two hydrodynamically separated reservoirs were discovered in Miocene beds with high yielding inflow containing more than 90% CO_2, and from the deeper horizons low yielding, non-combustible gas inflow (Szentgyörgyiné et al. 1999c).

Exploration wells have been drilled on the gravitaty maximum delineated between Sarkadkeresztúr, Méhkerék and the state border since 1974, and discovered mainly natural gas, along with some oil as well (Juhász, Kummer ed. 1997). A number of other successful exploration operations were carried out in the second half of the 1970s: the CO_2-rich gas reservoir of Berettyószentmárton was discovered in 1978 (Szentgyörgyiné et al. 2012b). Also in 1978 the Mezőpeterd natural gas occurrence and the Mezősas oil and natural gas field became known. The detailed exploration of the part of the

area was completed by OKGT in 1991 (LAWSON et al. 1991, KŐRÖSSY 1991). The residual anomaly map edited by using gravity data called the attention to the Biharugra area. The drilling exploration of the area started in October 1974, and a natural gas field was discovered by the Bihu–3 well in 1979 (KŐRÖSSY 2005b). The seven wells deepened in the Kokad area between 1985 and 1988 were drilled to explore the stratigraphic and structural traps of the lateral displacement zone in the Derecske Trough. The Kokad–1 (1985) and Kokad–5 wells (1987) discovered natural gas reservoirs (SZENTGYÖRGYINÉ et al. 2011c).

The exploration of the Mezősas West area was started by the MOL Hungarian Oil and Gas Plc in the spring of 1992. The purpose of the research was to collect hydrocarbon geological information on the deep zones situated to the west of the Komádi–Furta fields. The drilling exploration was started on the basis of the results of detailed seismic measurements in the Komádi–Mezősas area in 1987–89. Several structural traps could be identified on the map of the base Neogene, on the western side of the Mezősas structure. Nine of the 14 drilled wells proved to be productive (SZENTGYÖRGYINÉ et al. 2000). Result of the exploration in the 1990s was the discovery of the Nagykereki West natural gas occurrence as well (SZENTGYÖRGYINÉ et al. 2012b).

The Okány oil and gas field, and the Létavértes, Zsadány, Körösújfalu and Kótpuszta gas fields were explored as a result of the exploration project started after 2000 (SZENTGYÖRGYINÉ et al. 2010). The main goal of the exploration initiated recently by the Magyar Horizont Energia Kft. (Hungarian Horizon Energy Ltd) was to identify stratigraphic traps and unconventional hydrocarbons (JÁRAI et al. 2012b).

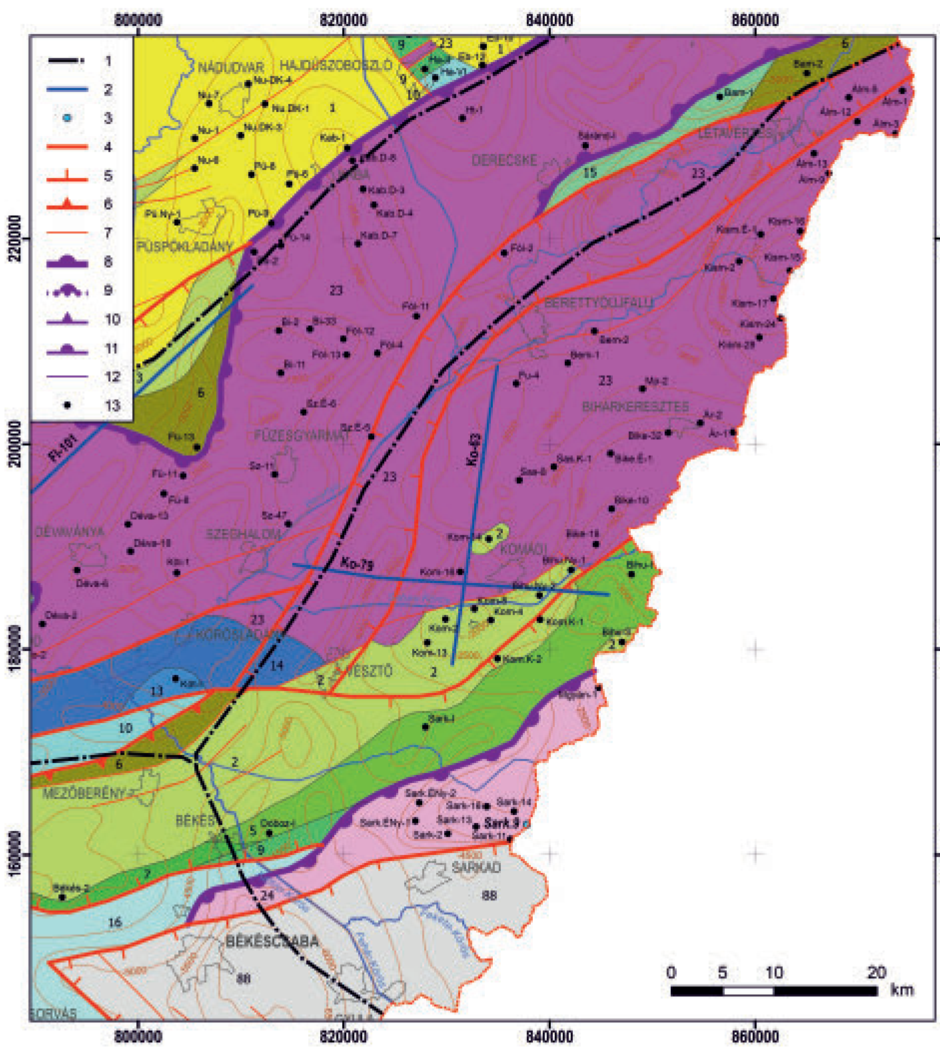


Figure 4.7.1. Pre-Cenozoic geological map of the Bihar area (HAAS et al. 2010)

Elements of legend: 1. Boundary of the sub-basins, 2. Trace lines of the sample 2D seismic sections in this chapter, 3. well with sample geophysical logs in this chapter, 4. second-order Cenozoic tectonic line, 5.second-order Cenozoic fault, 6. second-order overthrust, 7. third-order Cenozoic tectonic line, 8. first-order Mesozoic nappe boundary, 9. first-order Mesozoic nappe, buried, 10. second-order Mesozoic thrust fault, 11. second-order Mesozoic nappe, 12. third-order Mesozoic tectonic line, 13. well drilled the pre-Cenozoic basement

Legend for geological formations: 2. Senonian flysch, 3. Senonian continental, shallow- and deep-marine formations, 5. Lower Cretaceous platform limestone, 6. Lower Cretaceous basic volcanics and their reworked marine deposits, 7. Lower Cretaceous pelagic marls, limestones, 8. Jurassic to Lower Cretaceous pelagic limestones, marls, 9. Middle Jurassic to Lower Cretaceous pelagic limestones, cherty limestones, 10. Lower and Middle Jurassic pelagic fine siliciclastic formations, 13. Middle Triassic shallow-marine siliciclastic and carbonate formations, 14. Lower Triassic siliciclastic formation of fluvial and delta facies, 15. Low-grade metamorphic Mesozoic formations, 16. Mesozoic rocks in general, 17. Permian rhyolite, 23. Variscan metamorphic complex (gneiss, mica schists, amphibolite), 24. Variscan crystalline formations in general 88. inadequately evaluable or unknown basement

Geological overview

The Bihar sub-basin can be found in the Tisza Mega-unit area, the basement of which consists of three structural units, the Mecsek, the Villány–Bihor- and the Békés–Codru Unit. The Alpine evolution history of the three structural units was uniform up to the Late Triassic, when the microplate belonged to the European shelf of the Tethys. From the Late Triassic on, the shallow-marine shelf was broken up into pieces, and from this point on the evolution history of the three structural units became difference from the Mesozoic. Up to the middle period of the Cretaceous the area of the Villány–Bihor Unit, which constitutes the bulk of the basement of the Bihar sub-basin was relatively highly positioned between the deep basins of the Mecsek and Békés–Codru Unit. The zonal arrangement of

NE–SW direction could be formed as a result of the nappe formation and imbrication completed in the course of the Alpine orogenesis. In the course of the Late Cretaceous the Békés–Codru Unit (in the southern part of the Tisza Mega-unit) thrust over the Villány–Bihor Unit from the south forming a nappe (CSÁSZÁR 2005, HAAS, BUDAI ed. et al. 2014, 4.7.1).

The development of the current tectonic build-up of the area started in the syn-rift phase of the formation of the Pannonian Basin from the Karpatian Age up to the Sarmatian Age (FODOR et al. 1999). This was the time when the subsidence of the basement started in the area of the Derecske Trough located at the northern boundary of the area (Figure 4.7.2). The most intensive subsidence took place in the post-rift phase, during the Late Miocene. Several kilometre-long dislocations can also be identified in the Pannonian lacustrine sediments of the area; these movements, however, were finished by 8.2 million years ago (VAKARCS, VÁRNAI 1991). The rate of subsidence decreased subsequently, which is indicated by the small thickness of the Quaternary succession.

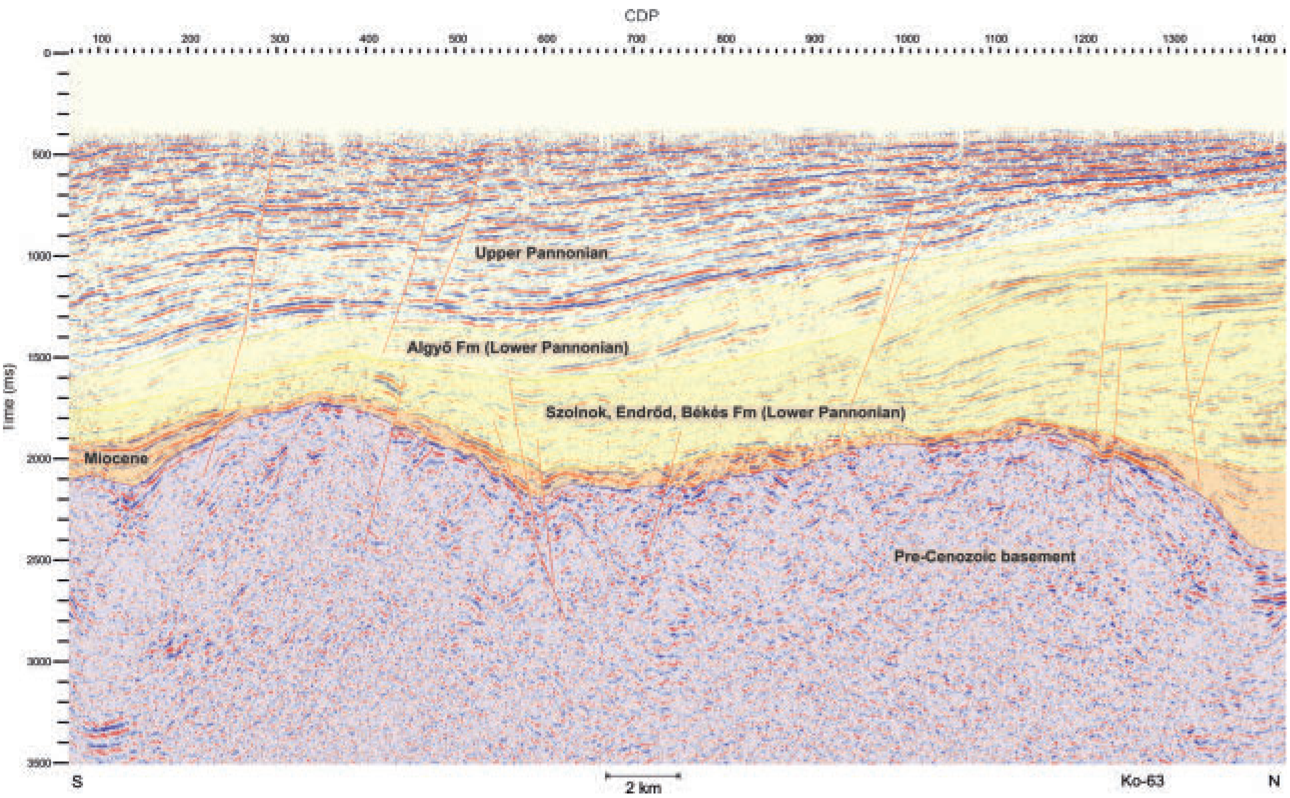


Figure 4.7.2. The seismic section Ko-63 crossing the Bihar area in approximately N-S direction

The Furta-Zsáka flat basement elevation can be seen on the right hand side of the profile (northern part); it sinks steeply to the north in the direction of the Derecske Trough. The basement elevation of the Komádi-Zsadány area can be observed in the southern part of the profile

The Cenozoic syn-rift tectonic component affecting the southern part of the area is a second-order normal fault of approximately E–W direction in the area between Sarkad and Sarkadkeresztúr. No data are available about the basement formations to the south of this fault (HAAS et al. 2010).

Basement formations

The Bihar sub-basin is situated in the area of the Villány–Bihor and Békés–Codru Unit of the Tisza Mega-unit. The pre-Mesozoic formations of the Sarkadkeresztúr Complex of the Békés–Codru Unit can be found in the southern part of the area. The maximum thickness of the formation consisting of migmatites of lithologically different types, some orthoclase–microcline granite, intercalated staurolitic mica schist and blastomilonitic gneiss (357 m) was revealed in the Sarkadkeresztúr Sark–2 well. Near the SW boundary of the sub-basin, in a small area, formations of uncertain stratigraphic position — conditionally classified into the Mesozoic — are also present. The great part of the basement is made up of the Körös Complex which belongs to the Villány–Bihor Unit, consisting of Variscan metamorphic formations (gneiss, mica, amphibolite) (HAAS, BUDAI ed. 2014).

Only a few data are available for the Lower Cretaceous Biharugra Calcareous Marl Formation which is a Mesozoic basement formation in the Villány–Bihor Unit. This formation is composed of dark grey calcareous marl, limestone and marl (BÉRCZINÉ MAKK 1996). The Lower Cretaceous, thick-bedded limestone of platform facies (Nagyharsány Limestone

Formation) is known from the Biharugra and Sarkadkeresztúr wells. Its maximum thickness (671 m) was revealed by the Sark–I well, where it overlies the Biharugra Formation (CSÁSZÁR 1996, HAAS, BUDAI ed. 2014).

The Senonian flysch classified into the Körös Formation is located in the middle part of the area having a NE–SW strike and overlying the Nagyharsány Limestone. It contacts with the other older formations along the Cenozoic structural lines. It can be observed in small areas in the eastern part of the area, where the Biharugra Bihu–3 well explored it at a depth of 2,295–3,000 m. In the Komádi area it has a small areal extent; the Kom–14 well drilled it in a thickness of only 35 m above the Variscan formations. The formation consists of dark grey, compressed siliciclastic rocks (sandstone, silt containing shaly marl, aleurolite, subordinately conglomerate) (SZENTGYÖRGYI 1996b). The maximum thickness is approximately 1,000 m (Kom–4 well). Age: Campanian–Maastrichtian.

Basin fill formations

In the course of the Early Miocene the area was a continental terrain; variegated clay with tuff/tuffite-intercalations, silt, sandstone and breccia–conglomerate beds were deposited, which were identified as the Madaras Formation (HÁMOR 1996). In the area it is known from the Komádi, Mezősas and Kismarja regions (in the Kism–28 well it is 136 m thick). The red clay-bearing polymictic breccia formations belong to this formation, the maximum thickness of which is about 500 m (PAP, S. verbal communication). The more exact age of the sediments cannot be determined.

The formations of the Great Hungarian Plain thought to be of Karpatian Age — except the breccia and conglomerate layers — were classified into the Kiskunhalas Formation (HORVÁTH, GYURICZA ed. 2012). This formation is made up of grey, dark grey, compact argillaceous marl, siltstone and sandstone of off-shore–open-water facies with gravel and tuffite intercalations ("Schlier succession" HÁMOR 2001). Its thickness exceeds 1,000 metres (SZENTGYÖRGYI, HÁMOR 1996a). The coarse clastic intercalations may have come from the erosion material of submarine ridges; erosion could have been

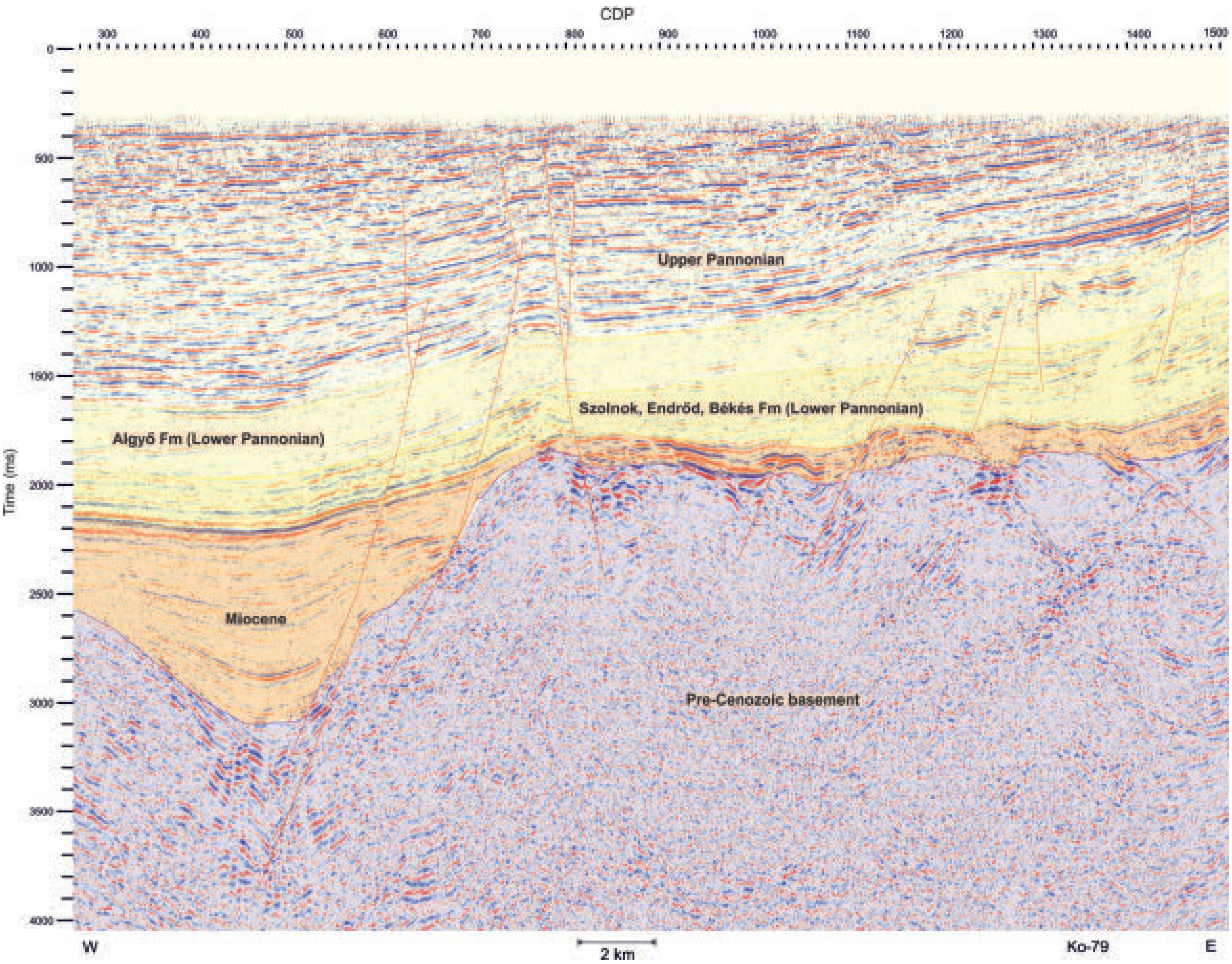


Figure 4.7.3. The seismic section Ko-79 crossing the Bihar area in approximately W-E direction

The profile crosses the approximately N-S striking tectonic zone, to the west of which the thick pre-Pannonian Miocene sequence of the Doboz-Vésztő-Darvas trough is situated. In the middle and eastern part of the profile the regional Komádi-Zsadány basement block can be seen which is in a higher position than the surrounding parts

triggered by structural movements. According to Szentgyörgyiné et al. (1999a) the N–S striking structural element running from the Komádi–12 well towards the Komádi–51 well is the borderline of the probable extension of the Karpatian formations (Figure 4.7.3).

The Badenian formations occur in a great part of the area. The typical clastic sequences start mainly with transgressional basal breccia, conglomerate, and form a transition upwards into sandstone and aleurolite layers, in which scattered tuff and volcanic tuff layers may also occur. The upward-fining breccia and conglomerate, sandstone beds were considered as the basal succession of the Badenian transgression, and were classified together with the overlying biogenic, bioclastic, lithothamnian–foraminiferal "Lajta Limestone" of the Abony Formation (Szentgyörgyi, Hámor 1996b). The thickness of the succession is very diverse; in the Komádi Kom–1 well it is merely 19 m, while in the Nagykereki Nkereki–1 well it exceeds 1000 metres (GeoBank of the Mining and Geological Survey of Hungary). The Badenian open-water pelitic sediments in the area and the surroundings were classified into the Makó Formation (Szentgyörgyi, Hámor 1996c, Hámor 1998). The validity of this formation was questioned (Magyar 2009), and in our opinion the fine-grained siliciclastic sediments referred to above and the dark grey marl occurring on the deeper, sub-marine ridges are the equivalents of the Baden Clay Formation in the Great Hungarian Plain. The "Upper Leithakalk" of the Great Hungarian Plain — developed on the upper, regressive wing of the Badenian sedimentary cycle — is present in the Bihar sub-basin as well, above local ridges of the basement. In the vicinity of Furta the carbonate sediments of the regressive, pelite–carbonate-tuff-bearing succession –overlying the basal beds of the Badenian sequence (comprising breccia, conglomerate and pebbly sandstone) — were classified into the Ebes Formation (Szentgyörgyiné et al. 1999c). The formation can be found near the western border of the area. Its thickness in general does not exceed 100 metres (Pap, S. verbal communication). According to the most recent concepts the Badenian calcareous algal limestone and calcareous sandstone layers (Abony and Ebes Formations) belong to the Lajta Limestone Formation in the Great Hungarian Plain, as well (Gyalog, Budai ed. 2004). The sequence — transected by the Ártánd Ár–2 well in a thickness of 50 m — was already classified into this formation (GeoBank of the Mining and Geological Survey of Hungary).

According to the information available at the present, the Sarmatian formations are missing in some parts of the Bihar area; they may have been eroded. The Komádi–8 well traversed a Sarmatian sequence confirmed by fauna, and based on this analogy it can also be assumed in the Komádi–7 sequence. According to the fossil fauna a Sarmatian succession was transected by Komádi–8 well; based on analogies it can also be assumed in Komádi–7 well (Szentgyörgyiné et al. 1999a). The Furta–2 and –11 wells penetrated clay marl, calcareous marl and sandstone sequences in a thickness of a couple of metres; they were conditionally classified into the Sarmatian (Hajdúszoboszló Formation) by Szentgyörgyiné et al. (1999c).

The basin filling successions are intercalated by volcanics in several horizons. The volcanic intercalations, correlated with the middle rhyolite tuff (Tar Dacite Tuff Formation), are known from this area as well (for instance in the Badenian (NN5 zone) sandstone–silt sequence of the Sas–Ny–well in the Mezősas–West area) (Szentgyörgyiné et al. 2000). Thicker dacite- and andesite-tuff intercalations of the Middle Miocene sequence can be interpreted as the interfingering with the rocks of the Nyírség Volcanic Group (Gyalog, Budai ed. 2004). The age of the Group in the Bihar sub-basin is most probably Badenian and Sarmatian.

Following the pre-Pannonian Miocene the area became continental terrain, the formerly deposited Miocene formations were eroded in a mosaic-like pattern. The pre-Pannonian Miocene succession or locally older formations (for instance on the Upper Cretaceous fauna-bearing marl in the Komádi–10 well) are unconformably overlain by the Pannonian beds. The basal sediments, i.e. abrasion conglomerate, sandstone and subordinately breccia of shoreface facies (Békés Conglomerate Formation) are made up of the material of the basement rocks; their areal extension is restricted to the surroundings of the islands existing in the early periods of the Pannonian only. The thickness of the Békés Formation does not exceed 100 metres (Gajdos et al. 1996). The presence of the formation is mentioned merely from the Biharkeresztes area (Szentgyörgyiné et al. 2010, Vakarcs, Várnai 1991). The basal calcareous marl formation (Tótkomlós Calcareous Marl Member) of the Lower Pannonian open-water marl (Endrőd Marl Formation) is not present in the entire region, either. Other sediments of the Endrőd Formation are also missing locally (for instance on the top zone of the Furta South structure), and their thickness hardly exceeds 20 metres at certain locations (Furta) (Szentgyörgyiné et al. 2010). In other places their thickness is considerable (for instance in Komádi Kom.K–1 well: 428 m). The turbidite sequences of the Szolnok Sandstone Formation occur above the latter. The thickness of the sequence — made up of the alternation of fine-grained sandstone and argillaceous marl — is 620 m in the Doboz–I well, whereas it is 250 m in the Sarkadkeresztúr–I well. It is characterised by the dominance of sandstones in the Komádi region. At the base of the Szolnok Sandstone thinner or thicker sandstone beds of the so-called "Szalonta Sandstone Sequence" can be found, forming a regional marker horizon. Above the "Szalonta Sandstone Sequence" erratically pinching out turbidite sandstone bodies and lobes can be found, which contain smaller or larger hydrocarbon deposits (Szentgyörgyiné et al. 2010). The thickness of the Algyő Formation — built up of a sequence of dark grey clay marl layers and deposited mainly in underwater slope environments (delta slope and basin slope) — may reach even hundreds of metres (Doboz–I well: 820 m, Sarkadkeresztúr–I: 755 m, Ártánd–2: 727 m). It overlies the Szolnok Sandstone Formation, and where the latter is absent, it rests on the Endrőd Marl Formation (Figures 4.7.2, 4.7.3). Thus, in the Mezősas West area the

Badenian sediments may also form the underlying formations (SZENTGYÖRGYINÉ et al. 2000). The characteristic thickness of the Lower Pannonian succession (Peremarton Formation Group) exceeds 1,000 m, in the Doboz–I well it actually exceeds 1,700 metres.

The thickness of the Upper Pannonian Újfalu Sandstone Formation in the area may reach even hundreds of metres (Ártánd–2: 860 m, Komádi Kom.K–1: 754 m). The Zagyva Formation, forming the stratigraphic overburden rock, is built up of sand, sandstone, silt, clay and clay marl layers of fluvial and lacustrine facies, containing carbonised plant remains. Its beds cannot be easily distinguished from the underlying Újfalu Formation (deposited in delta plain environment); lithologically and in geophysical well logs it is difficult to distinguish from the overlying Nagyalföld Formation, which is made up of bluish-grey sand and grey or variegated clay, comprising gravelly sand and lignite intercalations (GAJDOS, PAP 1996). The joint maximum thickness of the Zagyva and Nagyalföld Formations in Vésztő V–1, and Körösladány Köt–I wells is around 700 m, while in the Sarkadkeresztúr area the joint thickness of the two formations is merely 100–150 m. The joint thickness of the Nagyalföld Variegated Clay Formation and the overlying Quaternary sediments in the Zsáka Fu–5 well is 880 m, and substantially less elsewhere (Kismarja–26: 325 m, Kism.Ny–1: 306 m, in Mezősas the typical values are 200–350 m). The maximum thickness of the Upper Pannonian succession (Dunántúl Group) in the area exceeds 1,000 metres. The basin filling sediments can be easily traced on the seismic profiles crossing the area (Figures 4.7.2, 4.7.3).

In the early stage of the evolution of the Lake Pannon a NE transport direction can be assumed in the area. The upper part of the sequence (delta slope, delta plain, delta background) is made up of sandy–shaly sediments transported from the north–north-east. The increased proportion of sand in the delta background beds is most probably originated from an erosion activity nearby (SZENTGYÖRGYINÉ et al. 2010). The traces of denudation at the end of the Pannonian or infra-Pannonian denudation can also be detected (ERDEI et al. 1997b).

The Quaternary beds are made up of different fluvial formations, predominantly sand of river bed, point bar and flood plain facies, and clay-bearing flood plain beds. They are locally overlain by infusion loess and peaty lacustrine–paludal sediments. The lower boundary of the Quaternary sequence cannot be drawn with certainty. The thickness of the Quaternary beds mostly exceeds 200 metres, and based on the paleomagnetic measurements carried out in the neighbouring Vésztő well this boundary is at 480 m (KŐRÖSSY 2005b).

An overview of hydrocarbon geology

The Bihar area is the smallest unit of hydrocarbon explorations in Hungary, yet one of the richest in oil and gas fields. The area is situated along the eastern state border in NE–SW direction in a length of approximately 100 km, but in a width of merely 20– 25 km (Figure 4.7.4). The basement is separated from the Nagykunság and Hajdúság regions by a deep zone running from the Derecske Trough up to the Békés Depression in NE–SW direction. The Álmosd, Kismarja, Mezősas, Biharkeresztes and Sarkadkeresztúr basement highs expand under this region, each of them containing hydrocarbon reservoirs.

Source rocks

Hydrocarbons of the area can be derived from the matured organic material of sources in the deep troughs nearby, and have moved into their current position after a couple of kilometres migration upwards. The subsidence history model and the basic components of the hydrocarbon system of the nearby Békés Basin and Derecske Trough are found in Figures 4.4.6, 4.6.6.

Cretaceous and Triassic formations — according to the information currently available — cannot be considered as hydrocarbon source rocks. The CO_2 gases (Biharkeresztes South, Biharugra fields) known from Mesozoic reservoirs are assumed to be derived from the Mesozoic carbonates situating in great depths (SZENTGYÖRGYINÉ et al. 1999a)

The most important source rocks in the Bihar area are the Middle Miocene Badenian and the Upper Miocene Lower Pannonian pelitic and carbonate sediments. The Badenian pelitic–carbonate formations might be potential source rocks based on their disperse organic matter contents. Total organic carbon (TOC) values reaching occasionally as much as 5 wt% and the vitrinite reflectance shows thermal maturity (SZENTGYÖRGYINÉ et al. 1999a, 2010, CLAYTON et al. 1994a).

The sources in the northern part of Bihar area are mainly the Middle Miocene pelitic rocks situated in the deep zone of the Derecske Trough and the overlying Lower Pannonian argillaceous marls, marls. Based on the results of complex geochemical and vitrinite reflectance measurements carried out on the samples of the Derecske–I well the Miocene formations are in the dry gas generation zone, and the Lower Pannonian formations have also passed the main zone of oil generation. The vitrinite reflectance values reach 0.6%, 1.3%, and 2.0% at a depth of 2,470 m, 3,800 m and 4,210 m, respectively (HORVÁTH et al. 1988, SZENTGYÖRGYINÉ et al. 1999b).

Significant amount of hydrocarbons could have been generated in the Neogene sediments of the Vésztő Trough subsided into a depth of 4,000–5,000 m (mainly Miocene marls, argillaceous marls, as well as Lower Pannonian calcareous marls and subordinately argillaceous marls). The source area of the Mezősas West field hydrocarbons was also the Vésztő Trough,

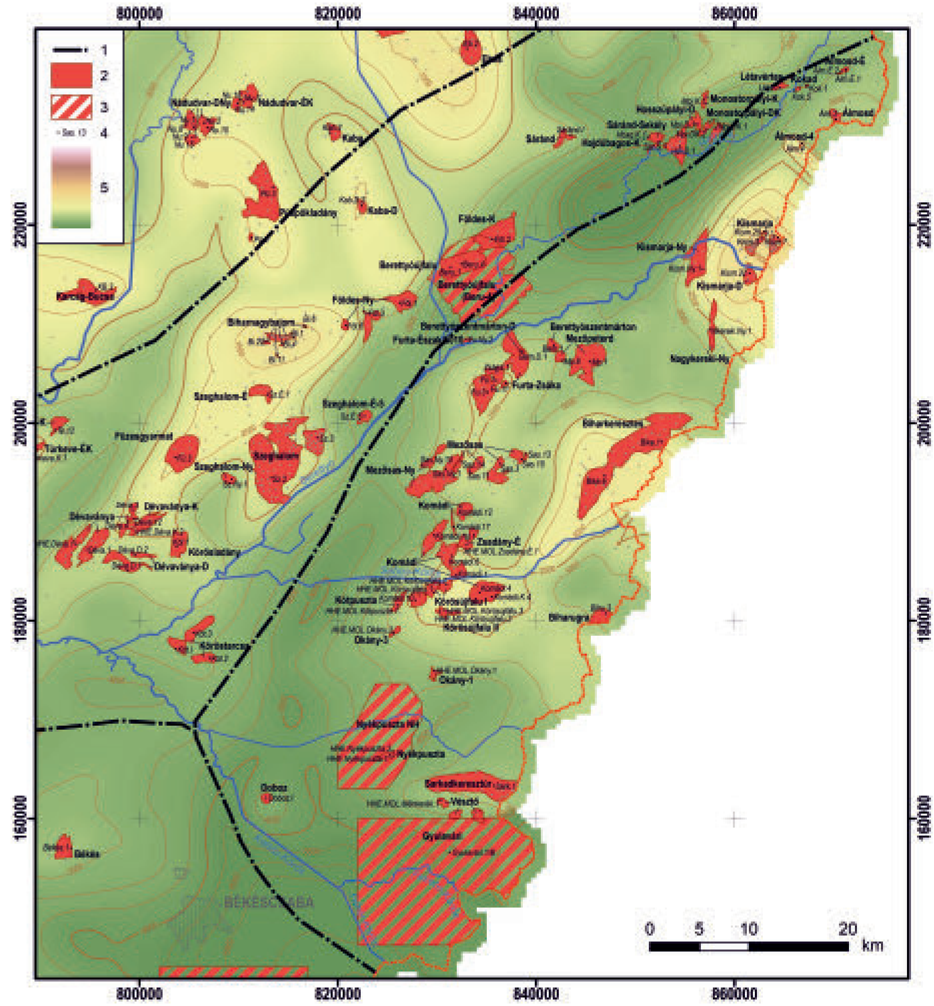


Figure 4.7.4. Location of hydrocarbon fields of the Bihar area

Legend: 1. Boundary of the sub-basins; 2. Conventional hydrocarbon field, 3. Unconventional hydrocarbon mining site; 4. Discovery well of hydrocarbon field; 5. Depth of the pre-Cenozoic basement

while the fluids of the Mezőpeterd–Furta fields could migrate to their current accumulation zone partly from the Derecske Trough, and partly from the Vésztő Trough (Szentgyörgyiné et al. 1999a, c; 2000). The same source rocks occur in the surroundings of the Bihar area, in the Komádi–Mezősas–Biharkeresztes Trough and the Békés Basin, as well.

Migration

The active source rocks located at great depths directly overlie the fractured, frequently brecciated formations of the crystalline basement in a significant part of the area, or they are in lateral contact with them tectonic elements. Hydrocarbons might have moved from the source rock towards a fracture network facilitating secondary migration. Migration also took place within the weathered–fissured crystalline basin basement rocks. In the wider area, Mesozoic carbonates might have provided good migration possibilities as well, just like the fractured crystalline bottom (Szentgyörgyiné et al. 2010).

A similarly good migration pathway might be potentially the base Neogene unconformity surface and the overlying Miocene basal conglomerates.

Hydrocarbon migration could have been made possible from the near basement to the accumulations formed in the higher lying reservoir horizons by the tectonic elements concerning the Pannonian succession. However those tectonic surfaces might have also played a role as barriers to migration (Szentgyörgyiné et al. 1999a).

Besides the buoyancy, the overpressure in the depth deeper than 3,000 m could have made allowed the generated hydrocarbons to migrate in multiple direction (upward, downward and laterally). The multidirectional migration of the hydrocarbons generated in the deep troughs and basins has been demonstrated by the subsidence, thermal and maturity history model calculations of Horváth et al. (1988). The migration was also influenced by the impacts of the morphology of the basin basement, and of the unconformity horizons in the overlying Middle Miocene and Pannonian sequences.

Reservoir rocks

The best reservoir rocks of the area according to the experiences as follows (LAWSON et al. 1989, 1991; SŐREG et al. 1991; SZENTGYÖRGYINÉ et al. 1999a, b, c, 2010, 2011c):

— Pre-Cambrian fractured, brecciated metamorphites,
— Mesozoic carbonates,
— Miocene breccia, conglomerate, sandstones,
— Pannonian sandstones.

The porosity of the Pre-Mesozoic (Pre-Cambrian/Palaeozoic) fractured, occasionally brecciated metamorphites is around 5%, in certain cases might reach as much as 15–22%. The development of the secondary reservoir porosity in crystalline rocks can be attributed to the tectonic stresses and movements and the erosional surface weathering processes. Miocene reservoirs in the Bihar area consist mainly of breccias, conglomerates and sandstones. The coarse debris is derived from the crystalline basement complex. Pannonian sandstone reservoirs belong primarily to the Újfalu Sandstone Formation, and to the Algyő and Szolnok Formations. Their genetics is diverse; pinching-out coastal sandstones and sandstones deposited on the delta front and delta plains are often found. The best reservoirs include the incised valley fills, the estuary sand bars and the meandering bed facies. Their respective porosity ranges between 7 and 29%, mostly 21–25%. Reservoir rocks may include the Tótkomlós Calcareous Marl Member of the Endrőd Marl Formation, as well (for instance the Furta field in the area).

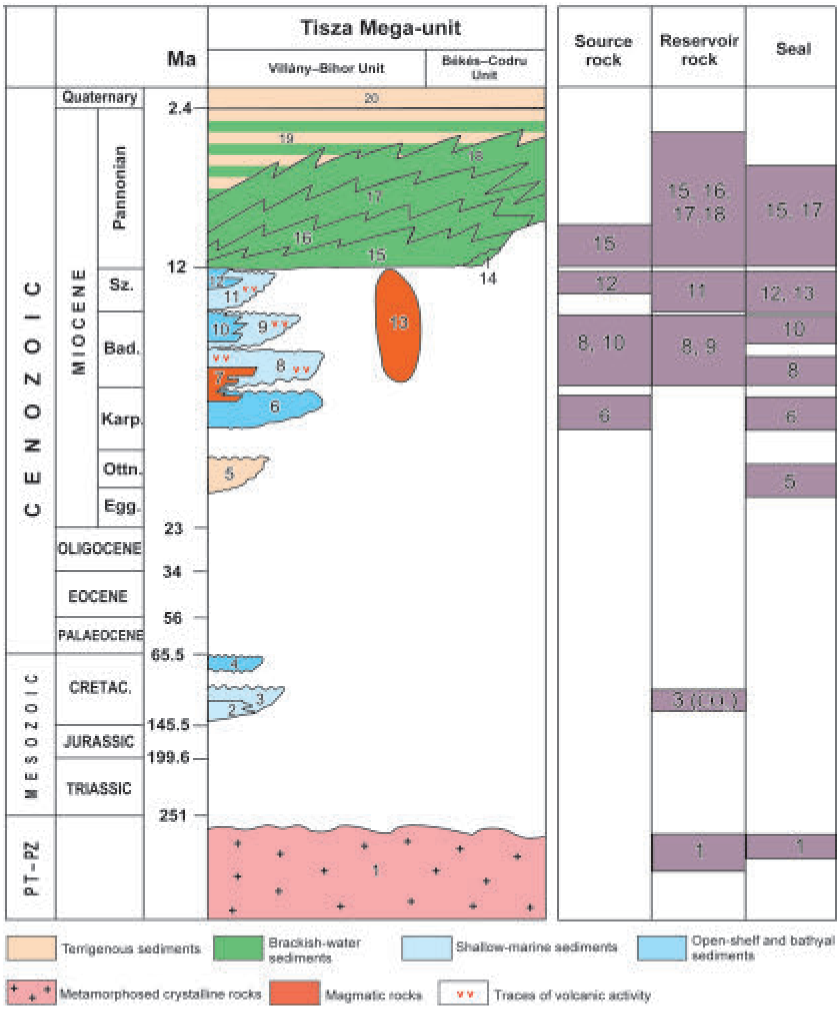


Figure 4.7.5. Lithostratigraphic units and the elements of hydrocarbon systems of the Bihar area

Lithostratigraphic formations indicated by numbers on the profile and their respective thicknesses (provided data are available). 1 Variscan crystalline and metamorphite succession (Sarkadkeresztúr Complex, Körös Complex), 2. Biharugra Marl Formation, 3. Nagyharsány Limestone Formation (0–700 m), 4. Körös Formation (0–1,000 m), 5. Madaras Formation (0–150 m), 6. Kiskunhalas Formation (0–500? m), 7. Tar Dacite Tuff Formation, 8. Abony Formation (>1,100 m), 9. Ebes Formation, 10. Baden Clay Formation (instead of Makó Formation), 11. Hajdúszoboszló Formation, 12. Kozárd Formation, 13. Badenian–Sarmatian volcanic rocks (Nyírség Volcanics Group,) 14. Békés Conglomerate Formation (0–? m), 15. Endrőd Formation (0–450 m), 16. Szolnok Formation, 17. Algyő Formation (maximum 750? m), 18. Újfalu Formation (0–760? m), 19. Zagyva–Nagyalföld Formation consolidated, 20. Quaternary formations

Seal rocks

Under local pressure conditions seal rocks comprise impermeable rocks: marls, argillaceous marls and siltstones. Their thin intercalations provide local sealing.

The fractured, weathered reservoirs of the Pre-Cambrian basement are sealed by Miocene marls, argillaceous marls, weathered, clayey tuff intercalations, or Pannonian deep-water marls and argillaceous marls. In case of lithological traps sealing is supported where the reservoir rock becoming impermeable, or by argillisation, or pinching-out. The seal rocks consist of the frequently occurring impermeable argillaceous marl and marl layers, intercalations in the Miocene conglomerate and sandstone reservoirs, or just the impermeable, clay-bearing matrix of the breccias, conglomerates acts as local seal rock. Within the Pannonian successions mainly the argillaceous marl intercalations form a capping (SZENTGYÖRGYINÉ et al. 1999a, b). The faults and fault zones serve not only as migration routes, but may provide a closure when they become impermeable and create a barrier to further migration (for instance Kismarja).

Trapping

Known hydrocarbon accumulations in the Great Hungarian Plain are mainly related to structural traps. The

filling of the traps was regulated by the impermeability–permeability conditions formed as a result of the difference of pressure on the opposite sides of the tectonic elements. The location, size and morphology of entrapment was influenced by several factors: the morphology of the pre-Cenozoic basin basement and the base Pannonian horizon, local maximums formed on them, and the pseudoanticlines overlying them, the impermeability derived from lithologic changes, thickening and pinching out of the reservoir beds, the sealing effect of faults, capillary pressure conditions and the hydraulic pressure and flow systems (CLAYTON et al. 1994a; SZENTGYÖRGYINÉ et al. 1999a, 2010).

In the Bihar area hydrocarbons migrated away from a deeper position to their trapping locations in accordance with the current morphological conditions of the basement and unconformity horizons. A part of the reservoirs can be found in pseudoanticline structures. The impermeable faults occasionally transversing the anticlines and the Miocene and Pannonian formations overlying them formed structural traps and can even divided the fields into hydrodynamically separated parts. Additional places to trapping are the pinching-out siliciclastic reservoir zones. Summarising, the area is characterised by the various combinations of the stratigraphic and structural traps, and the reservoirs bordered by faults on one or more sides (WÓRUM et al. 2010, SZENTGYÖRGYINÉ et al. 1999a). The lithostratigraphic units and elements of hydrocarbon systems of the Bihar sub-basin area of the Great Plain is shown in the Figure 4.7.5.

The hydrocarbon occurrences of the Bihar area

Álmosd. The oil and gas field was discovered by the Álm–2 well in 1977. The gas-water contact (GWC) in the free gas reservoir is at 2,366 metres below sea level (bsl) in fractured metamorphite. The combustible part of the natural gas is 63.9%, the calorific value is 24.3 MJ/m^3, the methane content (CH_4) is 61.1%, carbon dioxide (CO_2) content 34.4%, nitrogen content (N_2) 1.7%. The Álm–12 well (1981) discovered a multiple oil reservoir (M–PT horizon) developed in the metamorphic basement and in the overlying Miocene clastics. The oil-water contact (OWC) is at a depth of 2,482 metres bsl. The paraffinic oil is gas saturated (oil reservoir with gas cap), its density is 860 kg/m^3. The dissolved gas content is 130 m^3/m^3, the combustible part of the gas is 80.3%, CH_4 60.3%, CO_2 15.8%, N_2 3.9%.

Álmosd–4. Two free gas reservoirs were discovered in Variscan metamorphic basement rocks by the Álmosd–4 well in 1979. The GWC is at 2,292 m and 2,178 m bsl, the combustible part of the gas is 97.9%, the calorific value is 43.2 MJ/m^3, CH_4 82.75%, CO_2 0.05%, N_2 2%. The C_{5+} contain (hydrocarbon compounds with more than 5 carbon atomic numbers) of the gas is 61.8 g/m^3.

Álmosd North (Álmosd-Észak). The natural gas reservoirs are situated in twelve horizons. Reservoirs discovered by the Álmosd-É–1 (2006) and –2 (2009) wells in a depth between 1,006.5 and 1,339.5 metres bsl in the Újfalu Sandstone Formation sequence. In the Álm-É–1 well 10, in the Álm-É–2 well 2 free gas reservoirs has become known. The combustible part of the gas is 96.5–97.7%, the calorific value varies in a range of 38.7–38.9 MJ/m^3 .

Berettyószentmárton. The CO_2-rich gas reservoir of the Bem–1 well became known in 1978. The well was drilled down to the highest point of a closing dome structure. The reservoir rocks in the Middle Miocene sequence deposited above the crystalline basin basement is calcareous marl laminated with silt and fine-grained sandstone (SZENTGYÖRGYINÉ et al. 2012b). The GWC is at 2,360 m bsl. The combustible part of the inert contained gas is 12.98%, the calorific value is 4.7 MJ/m^3.

Berettyószentmárton South (Berettyószentmárton-Dél). The field was discovered by the Bem.D–1 well in 2014. Reservoirs are known from four horizons. The combustible part of the lowermost carbon dioxide gas reservoir formed in Miocene limestone is merely 4.5%, the calorific value is also low: 1.6 MJ/m^3. The carbon dioxide-content is 95.2%. In the Pannonian sequence three condensate contented gas reservoirs are known. The combustible part of the gas varies between 83.9 and 93.2%, the calorific value is between 34.5 and 39.5 MJ/m^3, CH_4 70.7–78.0%.

Biharkeresztes–Körösszegapáti. The natural gas field had discovered by the K–1 well (South-western reservoir group) in 1943, and was explored during the subsequently renewed operations by the Bike–1 well (North-eastern reservoir group) in 1980. The field is associated with a narrow, nearly NE–SW oriented structural high of the Variscan metamorphic basement. Nine reservoirs are known in the field. Two separated multiple reservoirs of high inert containing natural gas (NE and SW reservoirs) are situated in porous-fractured amphibolites and gneisses of Early Palaeozoic basement rocks and in the Middle Miocene Badenian–Sarmatian sandstone, conglomerate and limestone succession (VÖLGYI et al. 1985, JUHÁSZ, KUMMER ed. 1997). The GWC in the gas reservoir SW is at 1,433 m bsl, the combustible part is 34.1%, the calorific value: 13.4 MJ/m^3, CH_4 32.2%, CO_2 61%, N_2 4.9%, C_{5+} content 14.7 g/m^3. In the North-eastern reservoir with condensate containing gas the GWC is at 1,432 m bsl, the combustible part of the gas is 46.7%, the calorific value is 18.5 MJ/m^3, CH_4 43.6%, CO_2 46.5%, N_2 6.8%, the C_{5+} content is 16.95 g/m^3.

In addition to the above mentioned basement reservoirs, further 7 gas reservoirs (4 wet gas and 3 dry gas) are known in Upper Miocene Lower Pannonian reservoirs. The gas is accumulated in combined structural-lithologic traps. GWC-s are at 1,627.5–1,267.0 m, the combustible part of the gas is 83.3–95.7%, the calorific value is between 33.3 and 42.4 MJ/m^3, CH_4 75.0–87.5%, CO_2 0.4–4.4%, N_2 2.5–12.5%, the C_{5+} contents vary in a range of 7.5–131 g/m^3.

Biharugra. Two carbon dioxide gas reservoirs are known, which were discovered by the Bihu–3 well (1979) in the top zone of the Mesozoic succession and the overlying Middle Miocene formations. The Bihu3K1 carbon dioxide gas reservoir is situated in fractured, brecciated, Lower Cretaceous limestone with aleurolite intercalations. The GWC is at 2,254 m bsl. The combustible part of the gas is 7.3%, the calorific value is 2.7 MJ/m^3, CH_4 7.1%, CO_2 91.5%, N_2 1.2%. It has a minimum amount of paraffinic oil content. The CO_2 and the oil are not co-genetic, the CO_2 generated in the deep at high temperature swept out oil from the oil generating source rock during its migration (or from oil-containing beds) or was blended with oil hydrocarbons at the place of accumulation which was generated originally deeper (SZENTGYÖRGYINÉ et al. 2010). The reservoir rock of the Bihu3M carbon dioxide gas reservoir is made up of calcareous sandstone cemented breccia, the clastic material is limestone and metamorphic rocks. The formation is held to be of Miocene age based on the lithothamnium fragments. The GWC is at 2,156 m bsl, the combustible part of the gas is 7.4%, the calorific value is 2.7 MJ/m^3, CH_4 7.2%, CO_2 90.6%, N_2 2%.

Furta–Zsáka. The natural gas field was discovered by the Fu–1 well in 1957. Seven separated combustible natural gas reservoirs and a carbon dioxide gas reservoir are known in the metamorphic basement rocks. Each of them are multiple reservoirs. In the 7 free gas deposits of the crystalline basement the GWC is at 2,298–2,130 metres bsl. The combustible part of the gases is 11.6–91.7%, the calorific value is 4.3–39.7 MJ/m^3, CH_4 11.2–85.8%, CO_2 0.2–87.97%, N_2 0.5 and 9.5%. In two reservoirs (Pt–12N and Pt–12N1) inert gas is situated. In the carbon dioxide gas reservoir of Zsáka–1 well (Ptzsá1 CO_2) the GWC is at 2,202.5 m bsl, the combustible part of the gas is 0.9%, the calorific value is 0.8 MJ/m^3.

The gas-condensate reservoir Pz+M–1 is accumulated in multiple (Palaeozoic basement and the overlying Middle Miocene) reservoir, the gas can be characterised by high calorific value and condensate content. The GWC is at 2,170 m bsl, the combustible part of the gas is 90.3%, the calorific value is 40.2 MJ/m^3, CH_4 77.7%, CO_2 0.3%, N_2 9.4%, the C_{5+} content is 85.7 g/m^3.

Three combustible and one carbon dioxide natural gas reservoirs are known in *Middle Miocene reservoirs*. The M–É1N non-combustible gas reservoir is known from the Fu-É–1 well. The coarse clastic reservoir rock is coarse consists of metamorphic material silt containing conglomerate intersected with silt beds. The reservoir is bordered by faults from SW direction. The GWC is at 2,192.5 m bsl, the combustible part of the gas is 24.9%, the calorific value 9.4 MJ/m^3. The carbon dioxide content of the gas is 73.8%. The M-É1 CO_2 gas reservoir was formed in conglomerate. The GWC is at 2,175 m bsl. The combustible part of the gas is 9.1%, the calorific value is 3.4 MJ/m^3. The GWC in the M–8N non-combustible gas reservoir formed in Badenian tuffitic sandstone is at 2175 m bsl. The combustible part of the gas is 18.6%, the calorific value is 7.1 MJ/m^3, CO_2 80.5%. The reservoir rock of the M–1É combustible gas reservoir is conglomerate and tuffitic sandstone. The GWC is at 2,150 m bsl. The combustible part of the gas is 81.8%, the calorific value is 31.3 MJ/m^3, CH_4 76.7%, CO_2 12.5%.

Lower Pannonian natural gas reservoirs were also formed in the field. Of these, in the free gas reservoir of the Furta–13 well (Fu13–Pl1–2) the GWC is at 2,187.5 m bsl. The combustible part of the gas is 93.1%, the calorific value is 39.2 MJ/m^3, CH_4 78.1%, CO_2 4.8%. The reservoir was formed in sandy silt. The reservoir rock of the Fu–4 well non-combustible gas reservoir (Pl1–4N) is calcareous marl (Endrőd Marl Formation Tótkomlós Calcareous Marl Member). The GWC in the structural trap is at 2,164.5 m bsl. The combustible part of the gas is 10.3%, the calorific value is 3.7 MJ/m^3, CO_2 89.2%. The reservoir rock of the combustible mixed gas reservoir Pl1–1É in the Fu–1 well is the Tótkomlós Calcareous Marl. The GWC in the structural trap is at 2,135 metres below sea level. The combustible part of the gas is 58.5%, the calorific value is 22.3 mJ/m^3. CH_4 54.98%, CO_2 35.3%, N_2 6.2%.

Furta West (Furta-Nyugat). The natural gas reservoir was discovered by the Fu-Ny–2 well (1998). Middle Miocene reservoir rocks consist of alternating tuffitic silt and andesite tuff-tuffite beds. The GWC is at 2873 m bsl. The combustible part of the gas is 99.1%, the calorific value is 43.0 MJ/m^3, CH_4 84.2%. The density of paraffinic condensate is 786.9 kg/m^3 (SZENTGYÖRGYINÉ et al. 2012b).

Furta–Zsáka Fu–13. The natural gas reservoir of the Fu–13 well. The reservoir rock is 70 m thick, alternating succession with Pannonian light grey fine grained sandstone and dark grey silt (Algyő Formation). The GWC is at 2,073.5 m bsl. The combustible part of the gas is 85.5%, the calorific value is 38.6 MJ/m^3, CH_4 72. 4%, CO_2 10.8%, the C_{5+} content is 90 g/m^3.

Kismarja. The western reservoir group of the Kismarja oil and natural gas field was discovered by the Kism–3 well, while the eastern reservoir group of the field by the Kism–7 well in 1979 (VÖLGYI et al. 1985). Combustible natural gas and carbon dioxide reservoirs were known in the fractured, brecciated metamorphics of the Variscan pre-Mesozoic basement. Oil reservoirs with and without gas cap, combustible free gas and carbon dioxide gas reservoirs were discovered in the Upper Pannonian silt-containing sandstone. The GWC of the carbon dioxide gas (Ny-A reservoir) and natural gas (PT-NY-B) reservoirs sitting in the pre-Mesozoic metamorphics of the western field section is at 751 m and 724 m bsl. In the carbon dioxide gas reservoir the combustible part of the gas is 3.1%, the carbon dioxide content is 96.7% (VÖLGYI et al. 1985). The combustible part of the gas in the other free gas deposit is 64.7%, the calorific value is 26.0 MJ/m^3, CH_4 59.2%, CO_2 33.0%, N_2 2.3%. The C_{5+} content is 26.8 g/m^3. Both are multiple reservoirs in the basement rocks and in the overlying basal sediments. In the Upper Pannonian silt containing sandstone oil reservoirs are known with/without gas cap. The OWC of

the oil reservoirs of the western sub-field is at 742.5–664.6 m bsl. The density of the paraffinic-intermediate oil varies in the range of 821.5–912.6 kg/m^3. The combustible part of the dissolved gas is 5.5–92.6%, the inert content 7.4–94.5%, the calorific value is 3.1–37.2 MJ/m^3 (Völgyi et al. 1985). In the Upper Pannonian oil reservoir of the former eastern field the OWC is at 773 m bsl. The density of the intermediate oil is 833.7 kg/m^3. The dissolved gas content is 58 m^3/m^3, the combustible part of the gas is 94.3%, the calorific value is 44.4 MJ/m^3 (Völgyi et al. 1985). The GWC in the two oil reservoir with gas cap (one in the western, one in the eastern sub-field) are at 690 m, and 664 m bsl, respectively, the densities of the intermediate oil are 915 and 820 kg/m^3. Sulphur content of the oil is 0.1 and 0.6%, respectively. The dissolved gas contents are 60 and 78 m^3/m^3. Seven carbon dioxide gas reservoirs are also known in the Kismarja field in Upper Pannonian reservoirs.

Kismarja South (Kismarja-Dél). The oil and gas field has become known in 1984. Oil reservoir with gas cap and carbon dioxide gas reservoir are situated in the pre-Mesozoic basin basement fractured, brecciated metamorphics. The OWC is at 965 m bsl in the oil reservoir. The oil density is 960.6 kg/m^3. The dissolved gas content is 65 m^3/m^3, the combustible part of which is merely 3.4%, the calorific value therefore is very low as well: 11.2 MJ/m^3. A carbon dioxide reservoir is situated in the Middle Miocene clastic succession; the GWC here is at 965 m bsl, the combustible part of the gas is 3.8%, the calorific value is 1.5 MJ/m^3, CH_4 3.5%, CO_2 95.6%, N_2 0.6%. In Lower Pannonian sandstones a CO_2 reservoir and a natural gas reservoir was formed; in the deeper positioned carbon dioxide reservoir the GWC is at 924 m bsl, the combustible part of the gas is 2.7%, the calorific value is 1.0 MJ/m^3, CH_4 2.7%, CO_2 97.3%. The GWC in the natural gas deposit is at 828.5 m bsl, the combustible part of the gas is 71.4%, the calorific value is 31.1 MJ/m^3, CH_4 63.2%, CO_2 26.3%, N_2 2.3%. The C_{5+} content is 68.8 g/m^3. In Upper Pannonian sandstones oil reservoir with dissolved gas is known. The OWC is 753 m bsl, the density of the naphthenic oil is 964.6 kg/m^3. The combustible part of the dissolved gas is 56.5%, the calorific value is 21.3 MJ/m^3, CH_4 54%, CO_2 38.9%, N_2 4.6%. The C_{5+} content is 7.65 g/m^3 (Szentgyörgyiné et al. 1999b).

Kismarja West (Kismarja-Nyugat). The natural gas field was discovered by in 1996. The Kism-Ny–1, –2 and –3 wells drilled five free gas accumulations in Lower Pannonian and Upper Pannonian reservoirs (Szentgyörgyiné et al. 1999b). Reservoirs are tectonically closed by faults. Three dry natural gas reservoirs are known in Lower Pannonian sandstones. The GWCs are at 1,340–1,460 m bsl, the combustible part of the gas is 98.4–98.6%, the calorific value is 38.4–40.6 MJ/m^3, CH_4 88.6–92.3%, CO_2 0.9–1.2%, N_2 0.4–0.5%. The C_{5+} content varies in a range of 25.1–46.4 g/m^3. Two dry gas reservoirs are known in Upper Pannonian silt containing sandstones, the GWC are at 1,220 and 1,171 m bsl, the combustible parts of the gases are 96.5 and 95.6%, the calorific values are 42.4 and 44.5 MJ/m^3, CH_4 83.1 and 78.6%, CO_2 1.8, and 0.7%, N_2 1.7 and 3.7%. In the deeper positioned reservoir the C_{5+} content is 92 g/m^3.

Kokad. A natural gas reservoir was discovered by the Kokad–1 well (1985), and two gas reservoirs by the Kokad–5 well (1987) in the Upper Pannonian Újfalu Sandstone Formation. The one in the Kokad–1 well and the deeper lying reservoir of the Kokad–5 well locates on the same seismic horizon. Reservoirs are not interconnected, a fault can be shown between them. The traps probably were filled up through the faults with hydrocarbons generated in the deeper lying rocks (Szentgyörgyiné et al. 2011c). In the deeper lying reservoir of the Kokad–5 well the GWC is at 1,281 m bsl. The combustible part of the gas: 97.6%, the calorific value is 38.4 MJ/m^3, CH_4 92.2%, CO_2 0.6%, N_2 1.8%. The C_{5+} content is 27.8 g/m^3. In the higher positioned reservoir of the Kokad–5 well the GWC is at 1,137 m bsl. The combustible part of the gas is 97.0%, the calorific value is 35.2 MJ/m^3. CH_4 96.0%, CO_2 0.4%, N_2 2.6%. The GWC in the Kokad–1 well reservoir is at a depth of 1,175.5 m bsl. The combustible part of the gas is 97.0%, the calorific value is 40.6 MJ/m^3, CH_4 91.4%, CO_2 0.5%, N_2 2.5% The C_{5+} content is 112.3 g/m^3.

Komádi. The discovery well was the Kom–1 well (1974). Exploration of the 1990s provided productive wells as the Komádi-Ny–1, Komádi–10 and Komádi- K–4. The oil and gas reservoirs can be found in the fractured upper part of the metamorphic basin basement and in the overlying Middle Miocene breccia–conglomerate–tuffitic sandstone reservoirs, as well as in the Lower Pannonian rocks of the Endrőd Marl Formation Tótkomlós Calcareous Marl Member and the lenticular sandstones of the Algyő Formation (Kőrössy 2005b, Völgyi et al. 1985, Lawson et al. 1989, Szentgyörgyiné et al. 1999a). A total of 29 reservoirs are known on the field.

The crystalline basement rocks contain two oil reservoirs. In the deeper positioned accumulation the OWC is at 3,038 m bsl, the density of paraffinic oil is 810 kg/m^3, its sulphur content is 0.25%. The dissolved gas content is 155 m^3/m^3, the combustible part of the gas is 98.2%, the calorific value is 45.8 MJ/m^3, CH_4 72.5%, CO_2 0.6%, N_2 1.2%. The C_{5+} content is 40 g/m^3. In the higher positioned, tectonically closed basement reservoir contains oil with dissolved gas. The OWC is at a depth of 2,733.5 m bsl and the density of the paraffinic-intermediate oil is 833 kg/m^3. The dissolved gas content is 375 m^3/m^3, the combustible part of the gas is 99.0%, calorific value 44.6 MJ/m^3, CH_4 82.5%, CO_2 0.2%, N_2 0.8%. The C_{5+} content is 76.9 g/m^3.

In the multiple reservoirs (in the metamorphic basement rocks and in the overlying Middle Miocene sediments) 3 dissolved gas containing oil reservoirs are discovered. In the reservoir drilled by the Komádi–17 and –19 wells in the "B" block the OWC is at a depth of 3,079 m bsl, the oil is paraffinic with a density of 848 kg/m^3. The combustible part of the dissolved gas is 98.7%, the calorific value is 46.7 MJ/m^3, CH_4 81.6%, the C_{5+} content 165.5 g/m^3. The OWC of the oil reservoir explored by the Komádi–6 and –16 wells situated in the "A" block is at a depth of 2,273.5 m bsl. The density of the

paraffinic oil is 821 kg/m^3. The dissolved gas content is 39.9 m^3/m^3, the combustible part of the gas is 95%, the calorific value is 43.7 MJ/m^3. CH_4 77.6%, the C_{5+} content is 77.6 g/m^3. In the oil reservoir of the Komádi Nyugat–1 well the OWC is at 3038 m bsl, the oil is paraffinic, its density is 846 kg/m^3. The dissolved gas content is 20.3 m^3/m^3, the combustible part of the gas is 96.8%, calorific value: 45.9 MJ/m^3, CH_4 81.6% (LAWSON et al. 1989, SZENTGYÖRGYINÉ et al. 1999a).

Five oil and a natural gas accumulations can be found in Middle Miocene reservoirs. In the M–1 undersaturated oil reservoir of the "B" block the OWC is at 2,872 m bsl. The density of the intermediate oil is 874.2 kg/m^3. In the oil reservoir M–2 of the "B" block the OWC is at 2,584 m bsl. The density of the paraffinic oil is 818.2 kg/m^3. In the M–3 oil reservoir of the "A" block the OWC is at 2,219 m. The oil is paraffinic, its density is 847 kg/m^3. The dissolved gas content is high, 91.8 m^3/m^3. The combustible part of the gas is 97.7%, the calorific value is 43.9 MJ/m^3, CH_4 80.1%. In the oil reservoir of Kom-Ny–1 well the OWC is at 2,775 m bsl. The density of the paraffinic oil is 846 kg/m^3. The dissolved gas content is 20.3 m^3/m^3, the combustible part of the gas is 87.9%, calorific value is 46.4 MJ/m^3, CH_4 62.7%. A deep lying small dissolved gas containing oil reservoir is also known, where the OWC is at a depth of 2,824.5 m bsl. The density of the paraffinic oil is 821 kg/m^3.

The OWC in the three Lower Pannonian oil reservoirs can be found in a depth between 2,503 and 1,832.1 m bsl. The type of the oil in the two higher positioned reservoirs is paraffinic, in the lower one intermediate. The oil density is 792.2–897.4 kg/m^3. The characteristics of the gases of oil reservoirs: the combustible part is 93.7–98.6%, the calorific value is 39.3–40.3 MJ/m^3, CH_4 84.8–88.2%, CO_2 1.8–3.8%, N_2 1.4–4.5%.

In the case of the fifteen Lower Pannonian natural gas reservoirs the GWC is at a depth of 2,587.5–1,612 m bsl, the combustible part of the gases is 87.7–97.5%, the calorific value is 35.4–45.5 MJ/m^3, CH_4 75.25–89.3%, CO_2 0.01–5.9%, N_2 0.02 and 10.8%. The C_{5+} content varies between 8.7 and 136.4 g/m^3 (in three reservoirs this value is above 100).

Kótpuszta. The natural gas field was discovered by the Kpu–1 well in 2010. Five gas-condensate reservoirs were identified in Lower Pannonian turbidite (Szolnok Formation) sandstones. The thickness of the gas reservoir sandstones varies between 1.4 and 9.7 m (SZENTGYÖRGYINÉ et al. 2010). The combustible part of the gas is 93.2–94.2%, the calorific value is 35.9–37.7 MJ/m^3. The GWC in the lower, condensate containing free gas reservoir is at a depth of 1,949.5 m bsl, CH_4 85.8, CO_2 3.1, N_2 2.7%. The C_{5+} content is 25.8 g/m^3.

Körösújfalu. The natural gas field has six known free gas reservoirs in Lower Pannonian sandstone, mudstone and siltstone rocks. In the Körösújfalu–I area the Körös–1 and –7 wells were drilled. The Körös–1 well was deepened down between the southern wells of Komádi field the so called Komádi-K wells and discovered two gas reservoirs in the Lower Pannonian Szolnok Formation sequence. The GWC in the deeper reservoir is at a depth of 1,993 m bsl, the combustible part of the gas is 94.4%, the calorific value is 37.4 MJ/m^3, CH_4 83.1%, CO_2 2.9%, N_2 2.7%. The C_{5+} content is 23.9 g/m^3. The GWC in the upper reservoir is at a depth of 1,896 m bsl, the combustible part of the gas is 94.5%, the calorific value is 37.4 MJ/m^3, the methane, carbon dioxide and nitrogen content of the gas is the same as measured in the lower deposit. The Körös–7 well produced dry gas from the Lower Pannonian reservoir (SZENTGYÖRGYINÉ et al. 2010). The GWC in the reservoir is at a depth of 2,067 m bsl, the combustible part of the gas is 95.9%, the calorific value is 38.6 MJ/m^3, CH_4 83.0%, CO_2 1.0%, N_2 3.1%. The C_{5+} content is 54 g/m^3. In the Körösújfalu–II area there are two gas producing wells (Körös–2 and –3). The Körös–2 well discovered two gas reservoirs. In the lower reservoir the combustible part of the gas is 94.6%. the calorific value is 40.4 MJ/m^3. In the upper reservoir the combustible part of the gas is 95.3%, the calorific value is 37.8 MJ/m^3. In the reservoir explored by the Körös–3 well the combustible part of the gas is 94.5%, the calorific value is 38.2 MJ/m^3. The gas is escorted by light paraffinic condensate (SZENTGYÖRGYINÉ et al. 2010).

Létavértes. A natural gas field was discovered here in 2006. Léta–1 and –2 wells discovered a total of 25 single reservoirs in multiple levels in Upper Pannonian sandstone (Újfalu Sandstone Formation). One of the most significant is the Pl2–V6/1–3 gas reservoir with also condensate, situated in the upper three members of a sandstone bed group (SZENTGYÖRGYINÉ et al. 2011c). The GWC in the reservoirs is at a depth of 1,888.5–1,150.0 m bsl. The combustible part of the gases is 89.6– 97.9%, the calorific value is 34.2–38.6 MJ/m^3, CH_4 85.7–95.3%, CO_2 1.4–6.5%, N_2 1.7–3.8%. The C_{5+} content is 2.9–38.6 g/m^3.

Mezőpeterd. The natural gas field was discovered by the Mp–1 well (1978). Middle Miocene and Pannonian reservoirs are known here. The former reservoirs situated in the middle, clastic–pelitic and the upper, pelitic–carbonate sediments of the Middle Miocene succession, the latter are in the Lower Pannonian sandy–silt containing beds at the boundary of the Szolnok and Algyő Formations. All are single reservoirs. In the Middle Miocene beds 3 natural gas reservoirs are known. The lower two were formed in conglomerate or breccia, the reservoir rock of the upper accumulation is limestone, sandy limestone, calcareous sandstone (GAJDOS 1985b). The GWC is at 2,676.5–2,819.5 m bsl, the combustible part of the gas is 97.92–98.5%, the calorific value is 36.2–38.0 MJ/m^3, CH_4 89.9–94.6%, CO_2 0.0–0.4%, N_2 1–2%. The gases have low C_{5+} content 3.2–18.4 g/m^3. Five small sized natural gas reservoirs are known in Lower Pannonian formations. Reservoirs contain combustible natural gas and carbon dioxide gases. The GWC is at a depth of 2,150–2,555.5 m bsl. The combustible part of the gas in the reservoirs is more than 90%, the calorific value is between 34.5 MJ/m^3 and 39.4 MJ/m^3. In the deeper situated free gas reservoir the methane content is also high: 85.2%, CO_2 7.7%, N_2 1.95%. In the two carbon dioxide reservoirs the combustible part of the gas is very low, below 10% (GAJDOS 1985b), the calorific value is 2.6 and 3.6 MJ/m^3.

Mezősas. The occurrence was discovered by the Sas–well in 1978. Undersaturated oil, oil with gas cap and natural gas

reservoirs were identified in stratigraphic traps in the Variscan Palaeozoic metamorphic basement and in combined structural and lithological traps in Neogene pseudoanticline. Four oil accumulations can be found in the reservoirs of the Pre-Cambrian–Palaeozoic weathered, fractured metamorphic basement rocks (Völgyi et al. 1985, Lawson et al. 1991). The OWC is between 2,540 and 2,383.5 m bsl, the oil density is 825.8–830.0 kg/m^3. The oil in the lowermost reservoir is paraffinic-intermediate, in the other three reservoirs are paraffinic. In the three Middle Miocene oil reservoirs the OWC is at 2,280–2,413 m bsl. The oil in the lowermost and in the uppermost reservoirs are paraffinic, while in the middle horizon paraffinic-intermediate. The density is 777.0–842.7 kg/m^3, the sulphur content varies in the range of 0.1–0.5%. The two upper reservoirs consist of undersaturated oil. In the uppermost reservoir the dissolved gas content is 610 m^3/m^3, the combustible part of the gas is 87.7%, the calorific value is 44.7 MJ/m^3, the C_{5+} content is 147.6 g/m^3. In the middle reservoir the dissolved gas content is 70 m^3/m^3, the combustible part of the gas is 94.3%, the calorific value is 49.2 MJ/m^3. The C_{5+} content is 144.5 g/m^3. The dissolved gas in both reservoirs has high methane content as well (67.8%, and 71%). In the oil reservoir formed in the Lower Pannonian silt containing sandstone the OWC is at a depth of 2,286.5 m bsl. The density of the paraffinic oil is 831.5 kg/m^3. The OWC of the gas capped oil reservoir in the Lower Pannonian silt containing sandstone is at a depth of 2,240.5 m bsl. The density of the paraffinic oil 806.2 kg/m^3, the dissolved gas content is 180 m^3/m^3, the combustible part of the gas is 94.2%, the calorific value is 45.2 MJ/m^3, CH_4 78.9%, CO_2 4.5%, N_2 1.3%.

Mezősas West (Mezősas-Nyugat). The oil and gas field was discovered by the Sas-Ny–1 well in 1992. Combustible gas and condensate are known in the Middle Miocene coarse grained clastics. Accumulations were developed in structural traps bordered with reverse faults. The fractures separating the individual blocks played a dominant role in the trapping of the hydrocarbons. The accumulations are in multiple reservoirs under and over the basement unconformity. Reservoirs are in the fractured, brecciated rocks of the Variscan metamorphic basement rocks and the directly overlying Middle Miocene breccia, conglomerate and sandstone (Szentgyörgyiné et al. 2000). In the field 10 reservoirs are known of which 2 undersaturated oil reservoirs, 4 gas capped oil reservoirs and 4 gas condensate reservoirs can be distinguished. The OWC in the two undersaturated oil reservoirs is at a depth of 2,649–2,388 m bsl, the density of the paraffinic oil is 794–840 kg/m^3. The dissolved gas content is 322–168 m^3/m^3, the combustible part is 96–97.9%, CH_4 79.4–82.0%, $CO_2 \leq$ 0.6%. The OWC in the four gas capped oil reservoirs is at a depth of 2,876.5–2,602.5 m bsl, the density of the paraffinic oil is 806–840 kg/m^3. The dissolved gas content is 210–330 m^3/m^3. The combustible part of the gases is high, 98–99.6%, predominantly methane gas (80–85.4%). The carbon dioxide content is between 0.1 and 0.6%, N_2 0.4–1.8%. The GWC of the gas condensate reservoirs are at a depth of 2,700–2,421 m bsl. The combustible part of the gases is high, 84.5–98%, their calorific values is 35.0–44.5 MJ/m^3, predominantly methane gas (70.5–81.44%). The carbon dioxide content varies between 0 and 13%, N_2 1.9–5%.

Nagykereki West (Nagykereki-Nyugat). The natural gas field was discovered by the Nagykereki-West–1 well (1996). The reservoir rock is Upper Pannonian silt containing sandstone. Two reservoirs are known, the reservoir rock of the upper reservoir is a 4–5 m thick sandstone layer with lignite laminas, alternating siltstone and clay at the Zagyva–Újfalu Formation boundary. Dry gases are known in two horizons. Both reservoirs were developed in lithologically and tectonically closed traps. The reservoir parameters refer to excellent storage capacities. The gas is of very good quality (Szentgyörgyiné et al. 1999b). The GWC in the lower deposit is at 980 m bsl, the combustible part of the gas is 96.1%, the calorific value is 39.0 MJ/m^3, CH_4 87.8%, CO_2 3.6%, N_2 0.3%, C_{5+} 12.5 g/m^3. In the upper reservoir the GWC is at 695 m bsl, the combustible part of the gas is 96.9%, the calorific value is 38.4 MJ/m^3, CH_4 90%, CO_2 0.3%, N_2 2.8%, the C_{5+} content is 33.3 g/m^3.

Nyékpuszta. MHE Ltd identified the Nyékpuszta structure based on the interpretation of 3D seismic measures, and the Nyékpuszta–1 well was drilled down at the southernmost local maximum thereof. Significant hydrocarbon indication was known in the Middle Miocene succession by the drilling tests (Járai et al. 2010). The combustible part of the free gas reservoir of the Nyékpuszta–1 is 95.6%, the calorific value is 38.2 MJ/m^3, CH_4 81.6%, CO_2 4.3%.

Okány. The Okány–1 natural gas reservoir and the Okány–3 oil reservoir were discovered by wells. The GWC in the free gas reservoir discovered by the Okány–1 well (2006) in the Lower Pannonian succession is at 2,388.5 m bsl, the combustible part of the gas is 96,1%, the calorific value is 41.6 MJ/m^3, CH_4 83.8%, CO_2 3.4%, N_2 0.5%. The C_{5+} content is 66 g/m^3. The Okány–3 well (2008) discovered an undersaturated oil reservoir in Lower Pannonian sandstone. The trap is closed tectonically from the west and lithologically to the north and to the east (Szentgyörgyiné et al. 2010). The OWC is at a depth of 2,628 m bsl, the oil density is 891.1 kg/m^3.

Sarkadkeresztúr. The field was discovered by the Sark–1 well in 1976. A sometimes maximum 10 metres thick oil phase containing gas reservoir was formed in the upper, fractured, weathered zone of the Variscan crystalline basement and in the sporadically overlying Miocene, Sarmatian sandstone–limestone–conglomerate beds (Sarkad reservoir); the other reservoir rock is built up of Lower Pannonian sandstones (Szalonta reservoir). The type of the trap is stratigraphic in the metamorphic basement combined structural and lithological in a Neogene pseudoanticline (Völgyi et al. 1985, Juhász, Kummer ed. 1997). The geophysical well logs typical for the area can be seen on Figure 4.7.6. The “Sarkad” oil reservoir with gas cap developed in the basement rocks and in the overlying Middle Miocene sediments. The OWC is at 2,850 m bsl, the OGC is at 2,846 m bsl. The density of paraffinic-intermediate oil is 814 kg/m^3. The combustible part of the cap gas is 99.0%, the calorific value is 42.3 MJ/m^3, CH_4 84.3%, CO_2 0.6%, N_2 0.4%, the C_{5+} content is 32.2 g/m^3. In the Lower Pannonian sandstone reservoir (bottom to top) 3 free gas and 1 oil with gas cap reservoirs were discovered. The lowermost of

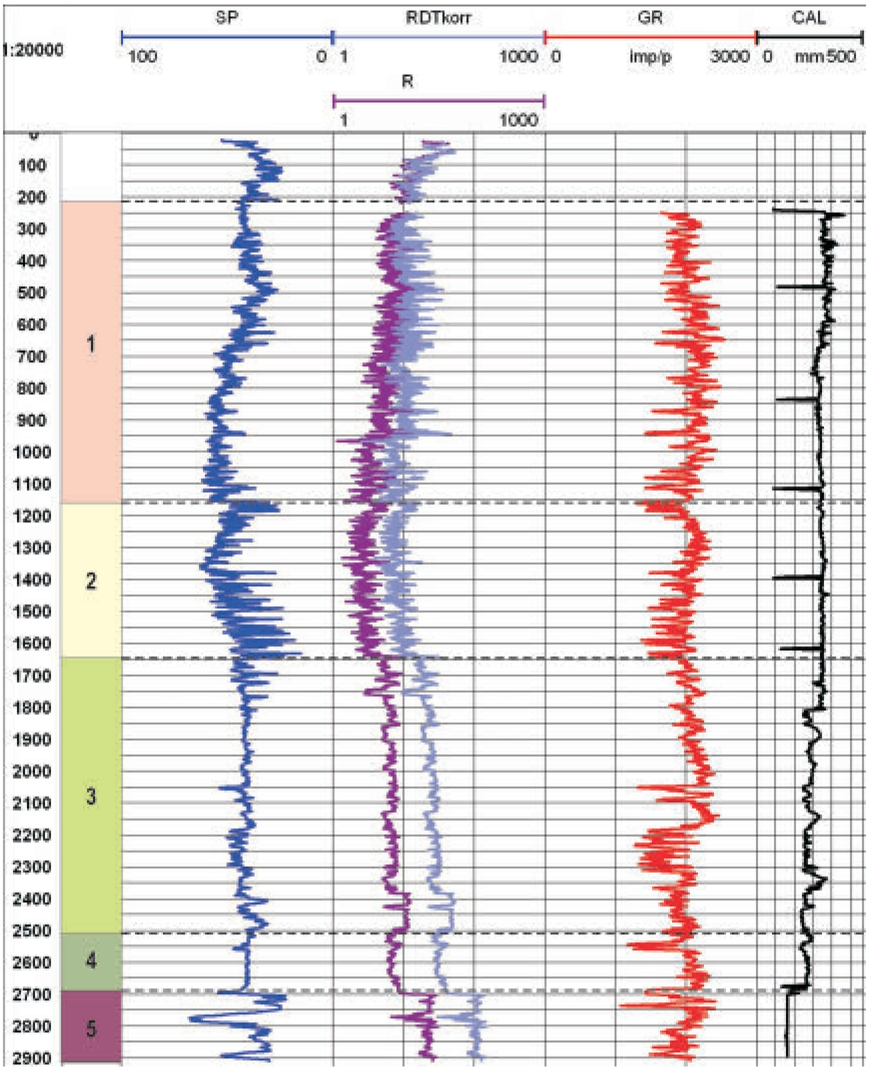


Figure 4.7.6. Geophysical well logs of the Sarkadkeresztúr Sark-9 well

Legend: SP: spontaneous potential, R,RDT: electric resistance; GR: natural gamma-ray; CAL: caliper log profile. Stratigraphic column: 1. Újfalu Fm (Upper Pannonian), 2. Algyő Fm (Lower Pannonian), 3. Szolnok Fm (Lower Pannonian), 4. Endrőd Fm.(Lower Pannonian), 5. Variscan basement

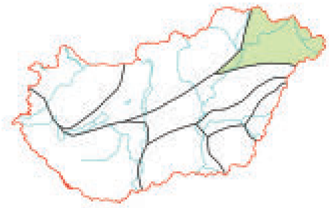
them is the Szalonta North natural gas reservoir, formed in structural/ lithologic trap of a Neogene pseudoanticline. The GWC is at a depth of 2,775 m bsl, the calorific value of the gas is 43.0 MJ/m^3, CH_4 73.2%, CO_2 6.2%, N_2 0.6%. The C_{5+} content is 25.9 g/m^3. In the two single reservoirs above the Szalonta reservoir the GWC is at a depth of 2,609 and 2,560 m bsl. The combustible part of the gas is 91.6 and 92.7%, the calorific value is 41.1 and 32.8 MJ/m^3, CH_4 78 and 91%, CO_2 7.6 and 6.7%, N_2 0.8 and 0.6%. The C_{5+} content is higher in the deeply positioned reservoir: 129.9 g/m^3. The uppermost oil reservoir with gas cap is situated in Lower Pannonian sandstone, in structural trap, the OWC is at 2,466.5 m bsl. The density of the intermediate oil is 785 kg/m^3. The dissolved gas content is 240 m^3/m^3. The combustible part of the cap gas is 94.1%, the calorific value is 41.0 MJ/m^3, CH_4 80.3%, CO_2 5.6%, N_2 0.3%. The C_{5+} content is 26.4 g/m^3.

Vésztő. Based on 3D seismic measurements carried out by the MHE Ltd the "Bird's nest" seismic anomaly group was interpreted on the southern slope of the Sarkadkeresztúr basement high in Lower Pannonian turbidite sandstones (Szolnok Formation). The re-evaluation of the Sark–2 well (1977) drilled here and qualified as dry earlier demonstrated the presence of combustible gas. Based on that results a well was drilled close to the centre of the anomaly. The HHE/Mol–Méhkerék–1 well discovered three gas saturated sandstone beds (JÁRAI et al. 2012b). The combustible part of the gas is 93.0%, the calorific value is 32.82 MJ/m^3, CH_4 31.1%, CO_2 6.4%, N_2 0.6%.

Zsadány North (Zsadány-Észak). The natural gas occurrence was discovered by the Zsadány-É–1 well in 2007. Two natural gas reservoirs are known by well tests in Lower Pannonian sandstones. Gases are of good quality, containing 93–97% HC contents (SZENTGYÖRGYINÉ et al. 2010). The GWC is at 2,066.5–1,637.0 m bsl, the combustible part of the gas is 93.2% and 96.6%, the calorific value is 41.7 and 40.9 MJ/m^3, CH_4 79.0, and 84.6%, CO_2 3.1 and 1.3%, N_2 3.7 and 2.1%. The C_{5+} content is 60.9 and 37.8 g/m^3 (the first values concern the deeper positioned reservoir).

Hydrocarbon exploration areas in Hungary — Nyírség sub-basin

Ágnes Cserkész-Nagy



4.8

Exploration history

The north-eastern part of the Great Hungarian Plain — mainly the Nyírség region — is less known and explored in terms of hydrocarbon occurrences. Due to the large extension and thickness of the buried volcanic deposits the area is risky from the perspective of hydrocarbon explorations, and no substantial hydrocarbon resources have been explored to date. So the region is considered a frontier area.

The deep drilling exploration of the Nyírség started in 1934 with the implementation of Tiszaberek Tb–1 well with total depth of 1,500 metres. It was followed subsequently by seven wells up to the 1980s: Nyíregyháza Ny–1 (1954), Gelénes–1 (1964), Komoró–I (1978) and Baktalórántháza Bakta–I (1984), and Hajdúnánás–1 and –2 wells in 1963 in the Jászság region. The Nagyecsed Necs–1 geophysical key well was drilled in 1973, but revealed only volcanics to the bottom depth of 4,001 m.

Surface geophysical measurements were started at the same time: the overviewing nationwide gravity and magnetic measurements of the Eötvös Loránd Geophysical Institute of Hungary (MÁELGI, ELGI) in the 1950s were followed by aerial magnetic measurements carried out by the Mecsek Ore Mining Company (MÉV) and the Central Office of Geology (KFH) in 1969. The gravity maps indicated the changes in the depth of the basement, and were useful in designing further seismic exploration and in interpreting the processed seismic data. The surface and aerial magnetic measurements played important roles in the research of the paleovolcanic structures. On the basis of the geophysical data the spatial distribution of the magnetic source could be determined including their depth from the surface and their susceptibility (Posgay 1967).

Between 1958 and 1962 the Geophysical Exploration Division of the National Oil and Gas Trust (OKGT) carried out seismic refraction measurements covering the whole Nyírség area. Connected to these refraction lines, MÁELGI started a five years long exploration programme of seismic reflection measurements along a grid in 1969. The seismic reflection measurements provided profiles of excellent quality and high resolution on the Pannonian strata and revealed the surface of the Miocene formations nicely, but did not provide any information about the pre-Neogene basement and the geological structures beneath. Telluric (TE) measurements provided to be useful also only up to the top of the volcanic rocks due to the shielding effect of the eruptive rocks. However, magneto-telluric (MT) and electromagnetic transient (TEM) methods occasionally were successful in penetrating the volcanic beds, and in this way a schematic geoelectrical model of the region could be set up. The schematic geoelectrical model included four distinct area types completed by the seismic data were used for generating a geological map of the region determined by geophysical parameters (Bodoky et al. 1977). Using these results three further hydrocarbon exploration wells were drilled in the southern part of the area (Csenger–1, Szamossályi–1, Gacsály–1) in 1989, but all proved to be dry. Up to now several hundred other wells with smaller depth were installed in the area, but only 36 wells exceed a depth of 300 metres.

Mol Hungarian Oil and Gas Plc renewed the surface geophysical explorations by seismic and magneto-telluric measurement between 2000 and 2010. Seismic reflection measurements were carried out along 38 profiles, in a total length of 531 km, and MT measurements were also made along the profiles by MÁELGI (Szentgyörgyiné et al. 2011a). In addition to an overview of the area the research aimed mainly at the gravity maximum at Kisvárda. Experimental seismic research was carried out here using wide angle reflection and velocity tomographic methods in 2002 to learn more about the thick volcanic formations (Hajnal et al. 2004). The intensive geophysical studies, however, were not followed by drilling due to the high level of risks involved.

Coevally with Mol Plc's surveying (2001–2009), Geomega Ltd, later its legal successor, Petro-Hungária Ltd, partly in cooperation with the HHE Nyírség Ltd carried out the exploration of the Szatmár (Nyírség–Szatmár exploration programme), and the Penészlek (Nyírség South exploration programme) areas. In the Nyírség–Szatmár area a total of 256 km long 2D seismic line network was measured and the Fehérgyarmat Fgy–2 exploration well was drilled. However, the Upper Pannonian sequence targeted by the well was not proven to be productive (WÓRUM et al. 2010a), in the Lower Pannonian – Miocene sequences gas indication was experienced, therefore the Miocene layers showed prospective for further exploration efforts.

The block called Hajdúdorog was separated from the Nyírség–Szatmár region as an independent exploration area in 2009, where the HHE Nyírség Ltd carried out further explorations. The HHE–Görbeháza Gh–1, and –5 wells were drilled here and the first one found small amounts of gas in a Lower Pannonian reservoir (VARGA 2010).

In the western part surveys were made between 2005 and 2014 again in the Hernád–I and –II exploration area by the HHE Ltd (and legal successors). The 3D seismic measurements of approximately 600 km^2 was followed by several productive exploration wells, which explored good quality combustible free gas accumulations and oil reservoirs with gas cap in Hajdúnánás, while at Tiszavasvári Miocene tight gas sand was explored.

In 2016 the scientists of the Hungarian Geological and Geophysical Institute (MFGI) carried out the experimental reprocessing and re-interpretation of 3 archive seismic profile surveyed by Geophysical Services (GES) Ltd in 2001–2002. The novel summarisation process based on the common reflective surfaces was primarily developed for the better imaging of the complex geological structures within the basement (YILMAZ 1999).

Three wells produce hydrocarbon operate in the area on three mining plot, but currently no active exploration efforts are underway. However, the draft of complex sensibility and vulnerability study was prepared in 2017 for 3 new proposed concession regions within the sub-basin — for Tiszlök, Nyíregyháza and Fehérgyarmat areas.

Geological overview

In the geological setting of the Nyírség sub-basin and its wider surroundings the several thousand metres thick Neogene and Quaternary sediments play the dominant role. The current basin-form was set up in the Miocene. However, only insufficient information is available on the tectonics and the geologic constitution of the basement. Based on the results of the complex geophysical measurements it can be assumed that the area is characterised by depressions and troughs more than 3,000 m deep and by basement highs encircled them (BODOKY et al., 1977), but the architecture of the pre-Neogene basement is still less known (Figure 4.8.1). According to the research of SZEIDOVITZ et al. 2003 the sub-basins are tectonically still active.

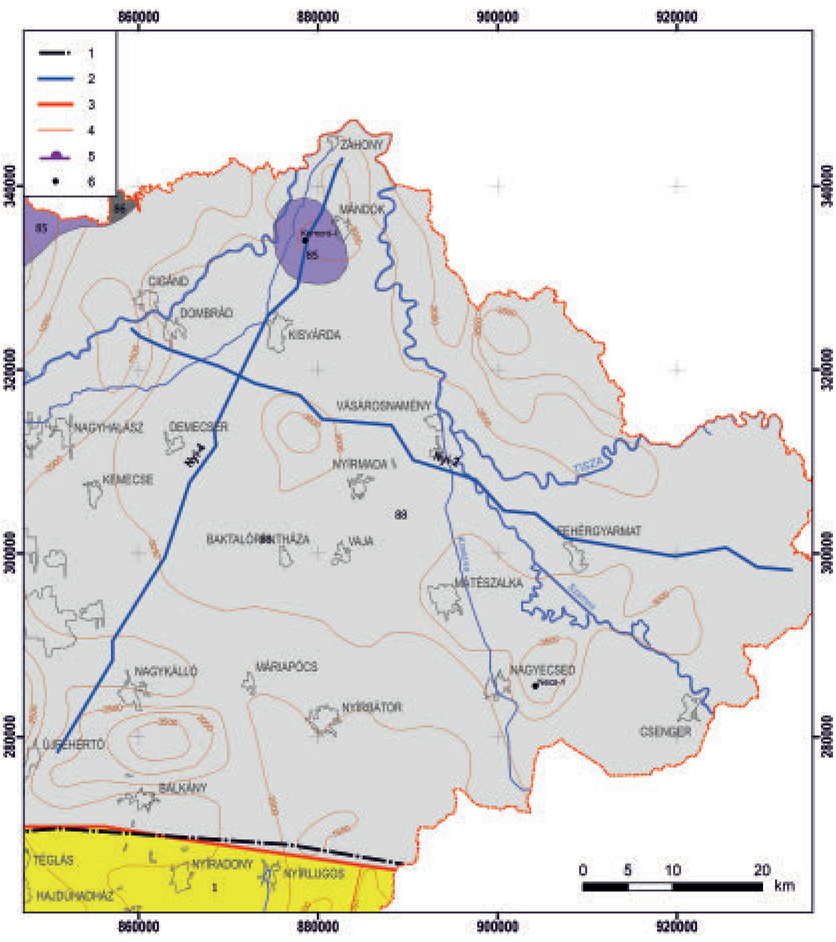


Figure 4.8.1. Pre-Cenozoic geological map of the Nyírség (HAAS et al. 2010)

Legend: 1. basin boundary, 2. 2D seismic lines, 3. second-order Cenozoic tectonic line, 4. third-order Cenozoic tectonic line, 5. second-order Mesozoic nappe inferred, 6. wells hit the pre-Cenozoic basement. *Legend for geological formations:* 1. Senonian–Palaeogene pelagic marls, flysch, 85. Middle and Upper Triassic platform carbonates, 86. Carboniferous–Permian continental siliciclastic formations and rhyolite, 88. inadequately evaluable or unknown basement

Several lithosphere terrains are in juxtaposed setting in the surroundings of the Nyírség which consists of geologically different successions: in the west the Bükk Unit of the Mid-Hungarian Mega-unit contacts with the Mecsek–Szolnok Unit of the Tisza Mega-unit originating from the Eurasian plate (Figure 2.3). The boundary between the mega-units is represented by the Mid-Hungarian Lineament tending in the SW–NE direction and the accompanying complicated tectonic zone (Mid-Hungarian Shear Zone) characterised by strike-slip, normal and reversed faults (CSONTOS, NAGYMAROSY 1998, KOVÁCS S., HAAS 2010). The course of the Mid-Hungarian Shear Zone which is relatively well known in Transdanubia and on the Danube–Tisza Interfluve is practically unknown in the Nyírség, and the north-eastern part of the Great Hungarian Plain because of the thick Miocene volcanic overburden, but is assumed to run on the southern border

of the Nyírség sub-basin (Figure 4.8.1). In the north-eastern part of the area the basement is most likely constituted by the Zemplén Unit of the Alcapa Mega-unit, separated from the Bükk Unit by the Hernád Line.

Basement rocks

The pre-Cenozoic formations of the area are known more in details only in the east of the Zemplén (Tokaj) Mountains. The oldest formations are the Variscan medium-grade metamorphics (mica and gneiss), which outcropped near Vilyvitány and Felsőregmec in a small area. Upper Carboniferous – Permian continental siliciclastic and rhyolite beds (Felsőregmec–3, Széphalom–2, Sátoraljaújhely Suh–8 wells), then Triassic formations were deposited on them with unconformity. In the Sátoraljaújhely Suh–8 and Komoró–I wells dark grey, dolomitic limestone, dolomite, clay-marl and mudstone were revealed. The Sárospatak–7 well explored 400 m thick Dachstein-type, thick bedded Upper Triassic platform carbonates. These formations altogether were subjected to a subsequent tectogenesis in the Cretaceous. The internal structure of the unit is characterised by SW vergence overthrusts/nappes(?) and folds, the development of which in any larger scale can be associated with the Alpine orogenesis (Haas et al. 2014).

Only two wells hitting the basement are known to the south of the Tisza. The Komoró–I borehole was drilled to the north of Kisvárda and crossed approximately 180 m thick dark grey quartziferous Palaeozoic strata under the Triassic (70 m thick) carbonate rocks, which were identified as formations of the Zemplén Unit (Haas et al. 2014). The revealed formations however can also be associated with the Mecsek–Szolnok Unit (Szentgyörgyiné et al. 2011a). The Necs–1 well in the south of the area perforated more than 3,000 metres thick volcanic deposits revealed Cretaceous diorite in the last 240 metres — between 3,760–4,001 metres — according to the most recent interpretations (MBFSZ Geobank data).

Based on the outcrops the northern third of the basin is assumed to belong to the Zemplén Unit, which show similarities with the Vepor Unit that is considered to be a part of the Alcapa Mega-unit originating from the African plate. The southern parts are hypothetically assigned to Mecsek Unit of the Tisza Mega-unit. This is supported by the clockwise rotation observed from the direction of the faults indicated on the southern part of the Neogene basement maps (Szentgyörgyiné et al. 2011a).

The presence of the Szolnok–Máramaros flysch belt is indicated by direct and indirect geological and geophysical data. Although no wells identified it directly, but the Lower Sarmatian acidic pyroclastic beds between 1,213 and 1,341 metres, revealed by the Gelénes–1 well contains clay marl and sandstone inclusions of Eocene – Lower Oligocene age confirmed by fauna. At the southern border of the area — around Nyírmártonfalva, Nyírlugos, and Penészlek — flysch formations are deposited as well in the pre-Neogene basement. Beside geological data the geophysical data also suggest that the formation appears in the Nagyhalász–Kállósemjén deep zone as well (No 22 on Figure 3.4) (Szentgyörgyiné et al. 2011b). The flysch (Nádudvar Complex) is separated from the surroundings tectonically and appears only in tracks. The positive flower structure typical for the area was formed by the Early Miocene transpressional wrench faulting movements.

A different interpretation of the flysch, — succession consisting of frequent alternations of clay-marl, siltstone, and sometimes calcareous sandstone layers, which contain fossils only sporadically — was presented by the experts of Petro-Hungária Ltd based on the paleontological and core tests of the Nyíl–1, Má–1, Pen–2 and Pen–3 wells. According to them the layers underlying the volcanic Miocene formations are rather of older Miocene age Karpatian) and are schlier type sediments, very similar in their lithofacies to the flysch. The paleontological fossils referring to the Palaeogene age could have been arrived into these beds by redeposition. Accordingly to this interpretation the formation is currently classified into the Kiskunhalas Formation of early Miocene, Karpatian age (Wórum et al. 2010b) (Figure 4.8.2).

Basin fill sediments

Probably since the Senonian compression tectonics was typical for the area, the elevated surface has become dry land, and sedimentation continued only in the flysch basins. Due to the intensive denudation in the Late Palaeogene – Early Miocene the surface of the basement has become morphologically slightly undulating peneplain sloping generally to the NE. Extension started in the beginning of the Miocene, and troughs opened up and lateral displacements occurred along NNE –SSW striking strike-slip faults. The most intensive subsidence took place in the Middle Miocene (in the Badenian and Sarmatian), associated with substantial volcanic activities. The basin was filled up during the Late Miocene.

Therefore, the Miocene formations overlying the erosional surface of the pre-Neogene basement are prevailing in the area, and are characterised by the dominance of volcanics (Figure 4.8.3 and 4.8.4). The oldest rocks are clays and sandstones of Karpatian age, which are intercalated in tuff layers in a total thickness of 300 metres. The shallow marine open sea fine grained pelitic and pelitic–carbonate sediments can be referred as Garáb Schlier (for instance in Bakta–I well) and Kiskunhalas Formation (for instance in Karos–2 well).

The volcanic activity, typical for the entire area, started in the Ottnangian and finished in the Pannonian. An igneous chain has been formed along the Mid-Hungarian Shear Zone as a continuation of the Örkény Trough in the east, which

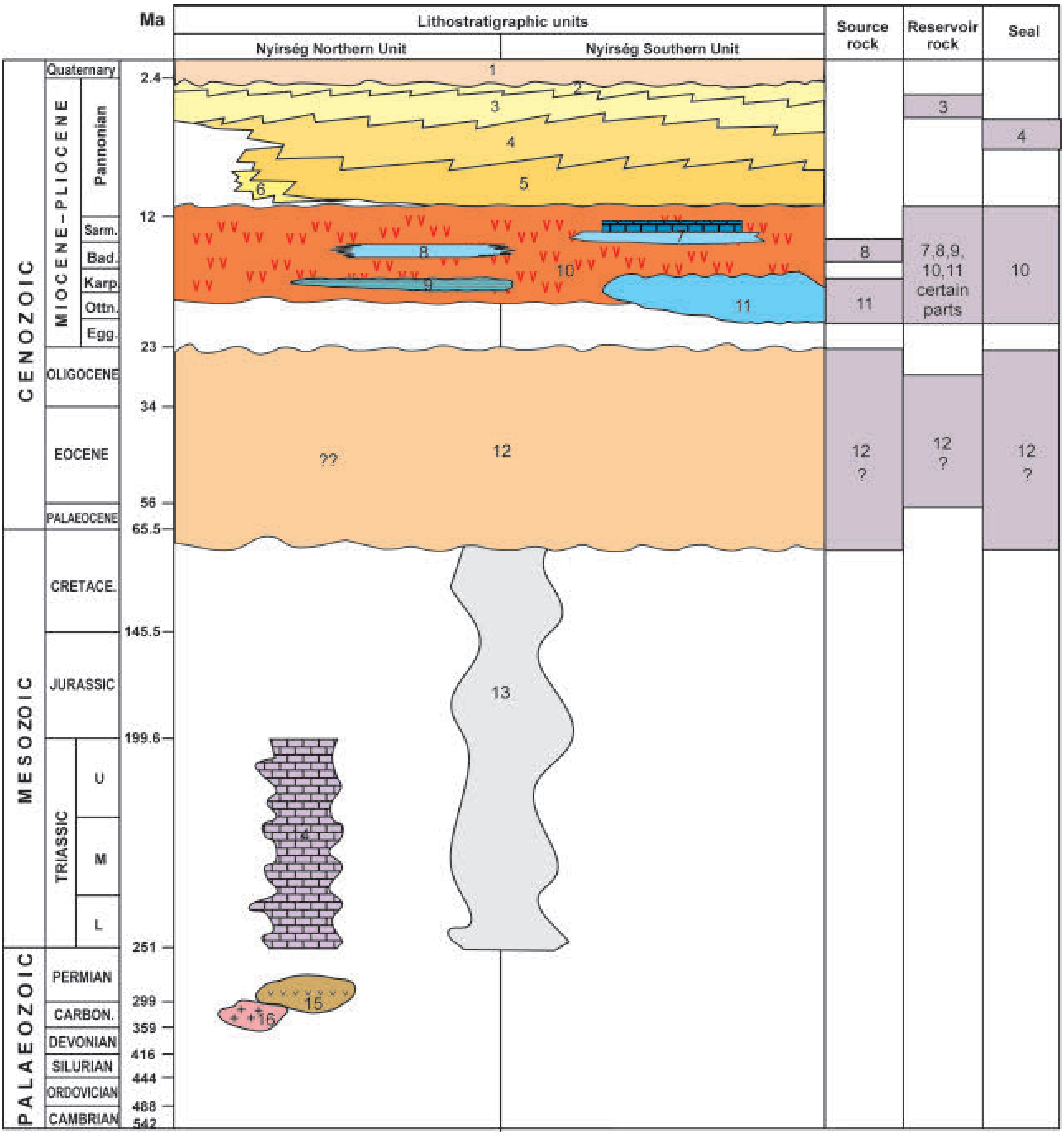


Figure 4.8.2. Basic stratigraphic column of the Nyírség and the elements of the hydrocarbon systems

1. Quaternary sediments, 2. Pannonian fluvial and lacustrine siliciclastic formations, 3. Pannonian delta front – delta plain siliciclastic formations, 4. Pannonian delta slope and basin slope formations, 5. Pannonian open lake calcareous marls, marls, argillaceous marls, 6. Pannonian basin-marginal clastic formations, 7. Sarmatian clays – argillaceous marls, calcareous sandstones, limestones, 8. Badenian argillaceous marls, sands, sandstones, 9. Karpatian shallow-marine, open sea fine grained siliciclastics and carbonates, 10. Miocene volcanics, 11. Lower–Middle Miocene schlier formations, 12. Senonian–Palaeogene flysch, 13. Unknown Mesozoic anchi-metamorphic formations, 14. Triassic carbonate rocks, 15. Upper Carbonferous – Permian terrestrial siliciclastic and rhyolite beds, 16. Variscian medium grade metamorphic rocks

belongs to the Tokaj–Nyírség volcanic belt (ZELENKA et al. 2004). The volcanic successions are getting younger from the south-west to the north-east. The Badenian and Sarmatian stage are represented mostly by intermediate (andesite, andesite tuff, agglomerate) and acidic (rhyolite, rhyolitic tuff, riodacite, dacite, dacite tuff) volcanics and volcano-sediments in 1,000–3,000 m thickness (Figure 4.8.5).

Extrusive rock variations can also be found in the surroundings of the volcanic eruption centres (for instance in Tiszatarján–1, Nagyecsed–1 wells). The volcanic formations are classified in four formation groups in this area: Mátra, Nyírség, Hegyalja and Tokaj Volcanics, the detailed description of them can be found in papers of GYALOG 1996 and GYALOG et al. 1999.

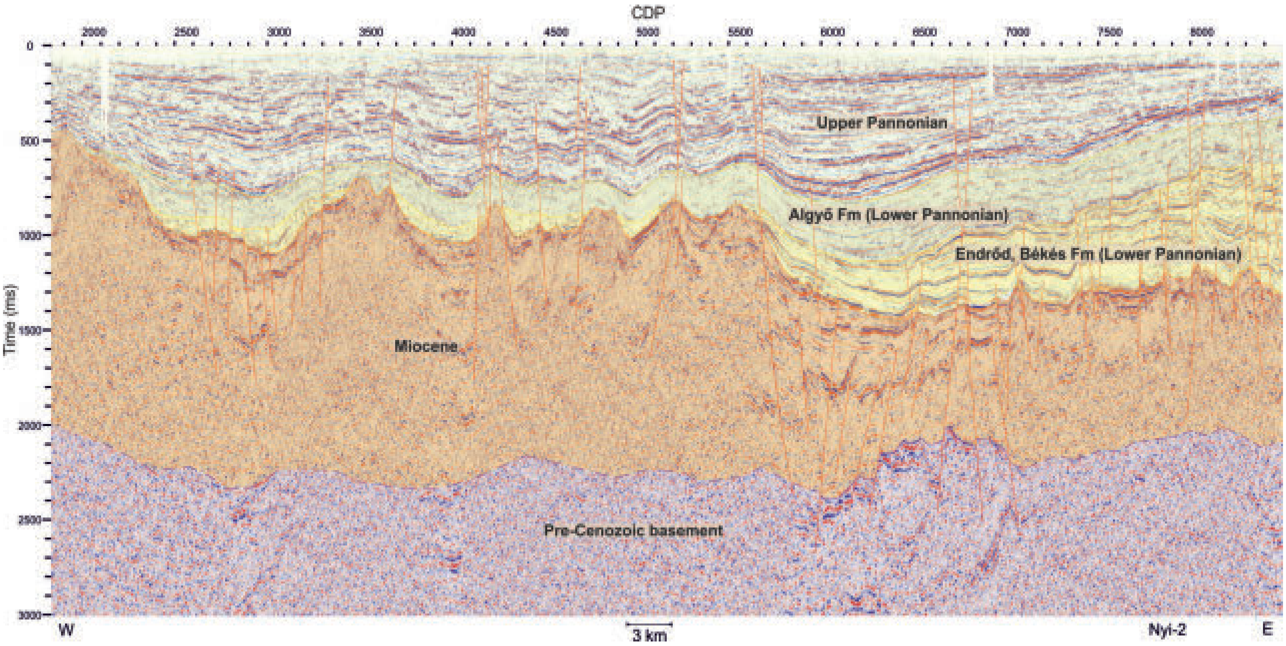


Figure 4.8.3. The seismic section Nyi-2 of E-W direction crossing the Nyírség area

The volcanic formations are intersected by sedimentary intercalations of different thicknesses: Badenian argillaceous marl – sand – sandstone sequence was explored by the Komoró–I well (Badenian Clay, Szilágy Clay Marl Formation). Sarmatian molluscan clay – argillaceous marl, calcareous sandstone, limestone succession (Kozárd Formation) was revealed by the Gelénes–1 and Tiszaberek–I wells. Reef limestone was also observed at the edges of the volcanic island ranges (Tiszaigal, Tiszakeszi). The thin, calcareous and siliciclastic intercalations identified from the south-eastern wells (Necs–1, Csen–1) are supposed to be patch reef formations of the Middle–Late Miocene shallow sea, as the Badenian Ebes (coarse grained sediments) and Abony (deeper water, psammitic sediments) Formation, as well as the subsequent Sarmatian Hajdúszoboszló and Dombegyháza Formations representing similar facies (WÓRUM et al. 2010a).

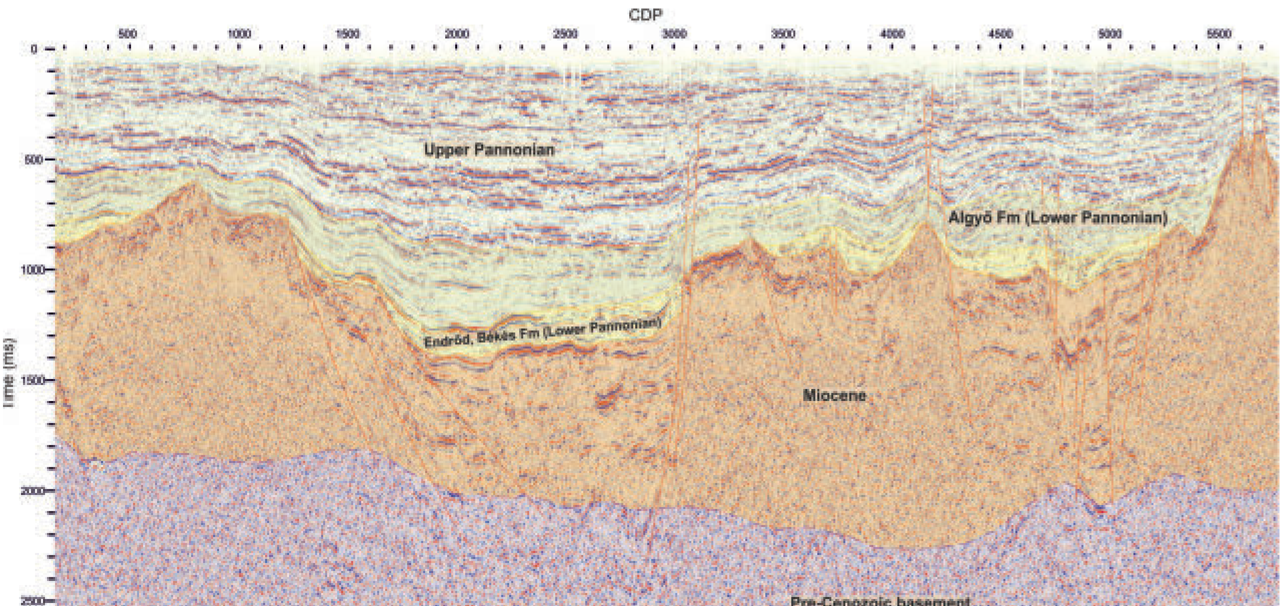


Figure 4.8.4. The seismic section Nyi-4 of N-S direction crossing the Nyírség area

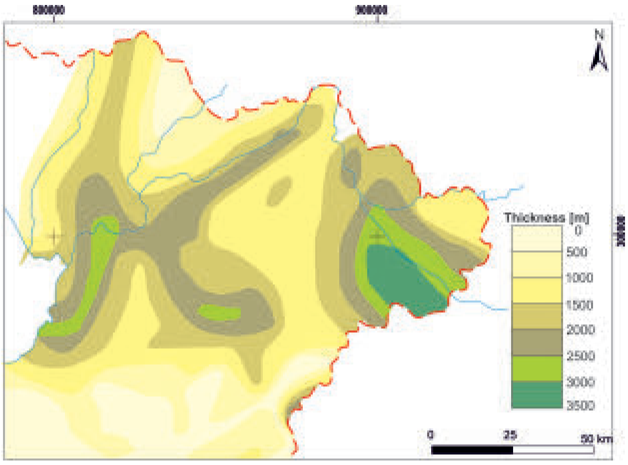


Figure 4.8.5. Isopach map of the Miocene formations in East Hungary excluding the Pannonian formations (adapted from SZÉKY-FUX et al. 2007)

In terms of its rate, the Neogene subsidence took place mostly in the post-rift (Pannonian) phase (HORVÁTH et al. 2015). The older Miocene beds are overlaid with slight unconformity by the Pannonian sediments, the thickness of which varies between 0 and 1,500 metres. A thick Pannonian sequence typical for the Great Hungarian Plain was developed mostly in the southern part of the area, while to the north of it the thinner beds of basin-marginal facies of the Lake Pannon are more common (terrestrial and nearshore clastic formations, occasionally paludal facies) and both the neritic marls and turbidites (Szolnok Formation), and the delta formations generally characteristic to the Pannonian Basin, the classic Algyő Formation are missing. For instance, the Lower Pannonian sequence is missing altogether from the Beregdaróc Bd–3 well, and the Upper Pannonian overlying the Sarmatian beds unconformably is only 30 m thick.

The Pannonian sequence starts with the Endrőd Marl Formation in the deeper basin areas that consists of condensed beds (calcareous marl, marl, argillaceous marl — the so-called "basal marl") deposited in the inner parts of the Pannonian Basin. The formation was present in the Hajdúnánás Hn–2 and Necs–1 wells in a thickness of more than 100 metres. The dark grey clay marl sequence of the Algyő Formation deposited in slope environment lies over directly the Endrőd Marl Formation in lack of the Szolnok Formation and which is difficult to separate from its underlayer, however unlike its typical facies, in the northern and eastern Nyírség it contains substantial amount of sand. The formation thickness in general is 100–500 m (Tb–I, Necs– 1).

The Upper Pannonian sediments are deposited continuously on the Lower Pannonian in general, but on the elevated highs (for instance at Görbeháza, Hajdúnánás, Szamossály), the Lower Pannonian formations are frequently missing. The Upper Pannonian formations, the Dunántúl Formation Group in the traditional sense are made up by the Újfalu Sandstone Formation, the Zagyva Formation which is difficult to separate from it, and the Nagyalföld Variegated Clay Formation. The Upper Pannonian sequence, deposited in delta front, delta plain and alluvial plain environments, keeps on having more sand upwards and is frequently intersected by lignite stripes or layers. The Upper Pannonian sequence is 800 m thick in average, but for instance on the elevated Samossály Structure are deposited merely 500 m thick Upper Pannonian beds.

These delta–fluvial and lacustrine successions are overlaid unconformably by 0–200 m thick Quaternary terrestrial–fluvial sand, gravelly sand, gravel, clay sequence, with drift sand intercalations in the Nyírség. The Holocene formations are only a few metres thick here. These consists of fine grained sandy, clay-bearing floodplain soils, paludal clay, peat, and mainly — still moving in the Nyírség up to date — drift sand.

Due to the suspected renewal of the structural elements of the basement the presence of similarly trending structural lines in the Miocene volcano-sediments are expected as well. The area is crossed by structural lines along of which the thickness of the Miocene sequence changes abruptly. The Pannonian deformation was of left lateral transtension nature and created negative flower structures. These faults cut through the Pannonian beds as well (WÓRUM et al. 2010 a).

An overview of hydrocarbon geology

The recently discovered hydrocarbon occurrences of the Nyírség sub-basin are located in the Tiszapalkonya Depression interpreted as a continuation of the Jászság Basin (Figure 4.8.6): Conventional natural gas was discovered in Pannonian sandstones by the Görbeháza and Hajdúnánás wells, unconventional tight gas in low permeability sandstone in the surroundings of Tiszavasvári, furthermore oil occurrence of lesser importance in fractured Miocene volcanics was found in the Hajdúnánás region.

Source rocks

Elements of the Neogene hydrocarbon system, which is the best known in the Pannonian Basin, are present in the Nyírség. The main source rocks of that are the Lower Pannonian and Miocene marls.

The average thickness of the Pannonian succession is 500–1,000 m, which appears in a great part of the area between the depth of 500–1,500 m, and the formation temperature varies between 50–90 °C (WÓRUM et al. 2010a, SZENTGYÖRGYINÉ et al. 2011a). Under such conditions their organic matter could not arrive to the maturity state necessary

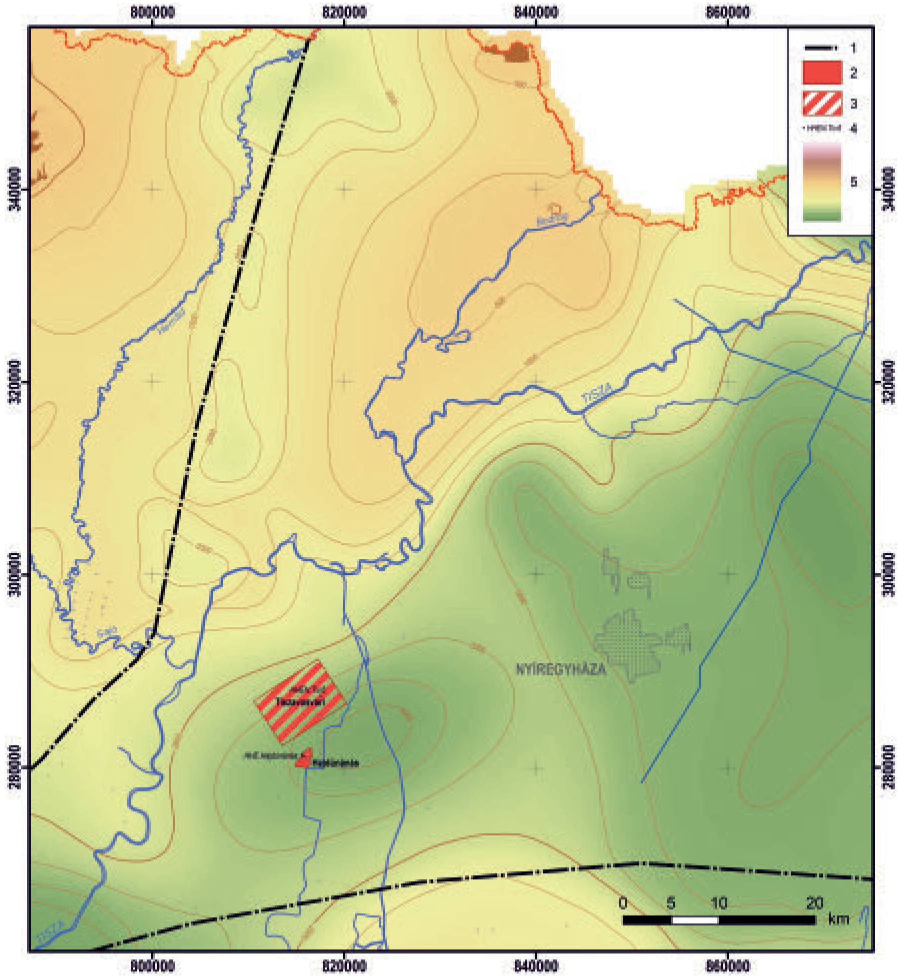


Figure 4.8.6. Location of hydrocarbon fields in the Nyírség
Legend: 1. Boundary of the sub-basin; 2. Conventional hydrocarbon field, 3. Unconventional hydrocarbon mining plot; 4. Discovery well of hydrocarbon field; 5. Depth of the pre-Cenozoic basement

for hydrocarbon generation even if the TOC (Total Organic Carbon) content is adequate. The wells around Tiszavasvári showed an organic matter-content of 1% in Pannonian deep water marls, but the Algyő Formation also has surprisingly high (although immature) organic matter-contents in some sections (up to as much as 2.0–2.5%).

The volcanics accumulated in greater depths in the 3,000–4,500 m deep, trench-like depressions cannot be counted as source rocks. The marine dark grey Badenian clay marls and silts (Badenian Clay, Szilágy Clay Marl Formations) intercalating and underlying the volcanitics and reaching significant thicknesses occasionally, can be taken into account as potential source rocks (Figure 4.8.7). The TOC tests of the Karos–2 well in the 449–747 m section (Karpatian stage Kiskunhalas Formation) provided a value of 0.07–5.62%, in average 1.59%, which suggests that the pelite layers explored by the well are classified as proper source rocks (Szentgyörgyiné et al. 2011a).

In the Miocene sequence under 2,600 m of the HHEN–Tiv–6 well mature source rocks with excellent organic matter content are deposited (up to as much as 4–6% TOC), to be associated with type III, terrestrial origin kerogen generating mainly gas (Figure 4.8.7) (Tóth, Wórum 2015). In the average stratigraphic depth of the Miocene formations the prevailing temperature condi-

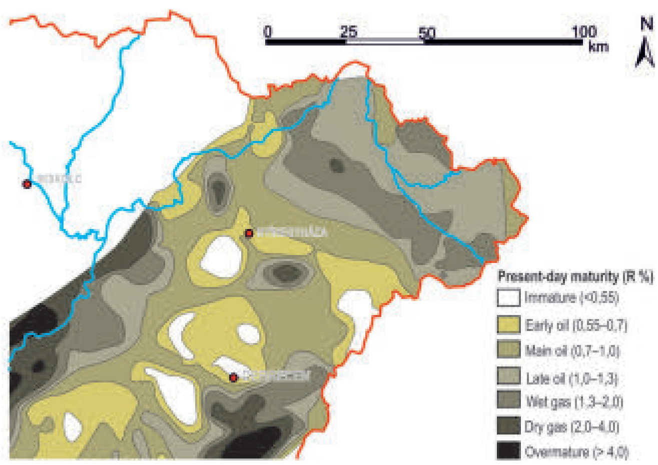


Figure 4.8.7. Depositional extent and maturity of the base Middle Miocene source rocks in the Nyírség adapted from Badics, Vető (2012)

tions are already sufficient to generate hydrocarbons. In the Bakta–I well 128 °C was measured at a depth of 2,812 m, while in the Komoró–I well the temperature was 156 °C at a depth of 3,310 m. Based on the data from the surroundings of Fehérgyarmat a 17–18 m/°C reciprocal geothermal gradient was determined which corresponds to the mean value in the Pannonian Basin (WÓRUM et al. 2010a).

In addition to all these during the evaluation of the source rocks the impact of the Miocene volcanism must be also taken into account as an enhancing factor in the paleo-geothermal gradient. It turns out from the geochemical tests carried out on the drill cuttings from the HHEN–Tit–1 and HHEN–Tiv–6 wells, that the Tiszapalkonya sub-basin has an extremely high geothermal gradient (65 °C / 1000 m), which results in the fact, that the upper boundary of the oil window represented by the 0.6% vitrinite reflectance value is supposed to be at a depth of around 2,000 m (TÓTH, WÓRUM 2015). The organic matters in the Neogene layers of the investigated wells contain typically Type II–III kerogen.

According to the current interpretations (HAAS et al. 2010) on the southern border of the Nyírség — in the vicinity of Nyírmártonfalva, Nyírlugos and Penészlek — flysch formations are set in the pre-Neogene bedrock. Beside direct and indirect geological data from a distance the geophysical data suggest that this formation may appear in several deep basins in the Nyírség, as well. These inferred Upper Cretaceous – Palaeogene sediments (flysch) seems to be promising in the deep zones of the sub-basins in terms of hydrocarbon generation based on domestic and country border line experiences.

Hydrocarbon generation potential of the Mesozoic and Palaeozoic formations older than the Upper Cretaceous is impaired by the fact that the basement formations in the Zemplén and Mecsek Sub-units are overmature (vitrinite reflectance value R_0>2.0), the hydrocarbon generated might have been given off earlier on, which could have been destroyed in the denudation period.

Migration

In the area — just like in the wider region –tectonic zones can be considered as the potential pathways for migration. Fault zones developed in the Savian orogenic phase recognised on the seismic profiles, and the faults related to their renewal in the Quaternary might provide only relatively short vertical migration routes (SZENTGYÖRGYINÉ et al. 2011a). The Pannonian deformation was of left lateral, transtension nature and created negative flower structures, the faults of which cut through the Pannonian formations formed Lower Pannonian structural traps. The latter deformation phase may play an important role in the tertiary, vertical migration of hydrocarbons, which are assumed to have been accumulated in the Miocene beds in the first place, into the Lower Pannonian sandstones (WÓRUM et al. 2010a). On the other hand, migration from the potentially existing other source rocks under the volcanic beds into the structurally higher positioned layers is quite questionable due to the great thickness of the volcanic rocks.

It is supported by the analysis of the formation tests carried out in the environs of Fehérgyarmat which suggested that the distribution of the salt content of groundwaters reflects a strong stratigraphic correlation. The NaCl content of the Lower Pannonian deep groundwater originating predominantly from a depth of 800–1,000 metres varies in the 2–5 g/l range, but in the Miocene top zone this value jumps up to 10–12 g/l. In the deeper layers of the Miocene sequence (~2,000 m Csen–1) a salt concentration of 18–20 g/l is typical. These figures suggest that no groundwater flow systems characterised by large-scale vertical flow were developed in, the deep groundwaters are practically hydrostatically stagnant (WÓRUM et al. 2010a).

Unconformity surfaces may also be taken into account as migration routes: inferred contact zones of the Palaeozoic–Mesozoic rocks and the overlying Cretaceous–Palaeogene flysch succession, the flysch and the Neogene, the Palaeozoic–Mesozoic and the Neogene formations, as well as the Pre-Pannonian unconformity observed in the seismic profiles.

Reservoir rocks

The Pannonian–Pliocene strata are separated from the older potential source rocks by thick volcanic beds in general, therefore they can only be reservoir rocks in exceptional cases, like for instance the Pannonian sands (Újfalu Formation) above the Hajdúnánás basement high. The Fehérgyarmat–2 well also explored non-consolidated beds with good porosity (>30%) and permeability (>500 mD) suitable for hydrocarbon storage in Late Pannonian formations consisting of thick sand layers of angular or rounded particles deposited in delta front and delta plain environment.

Hydrocarbons can be accumulated in some fissured, fragmented, occasionally tuffic sections of the Miocene volcanics as well (for instance the Görbeháza–Hajdúnánás field). The Nagyecsed–1, Csenger–1, Szamossályi–1, Gacsály–1 wells also detected fragmented, fissured volcanic sections characterised by variable extent of water supply, but no porous layers were identified in these wells which would be specifically suitable to store hydrocarbon. The HHEN–Tit–1 well also exposed water saturated strato-volcanic beds, in which gas indication was observed in multiple locations, but the formation has poor permeability.

The inferred flysch beds (Nádudvar Complex) may also be a hydrocarbon reservoir in certain specific locations based on the examples from the neighbourhood. The Palaeozoic–Mesozoic formations may also store hydrocarbons in the edge zones of the deep basins and in certain elevated areas.

The HHEN–Tiv–6 well discovered an unconventional reservoir. The more than 300 m thick gas containing sequence is intercalated by a number of sandstone layers. Their porosity is between 10 and 15%, but a detailed analysis showed that their permeability falls regularly short of 0.1 mD, and depends also on the formation pressure. Hydraulic well stimulation technics are necessary in order to bring the Miocene gas reservoir into production.

Seal rocks

The Miocene volcanic formations are practically very good seals. Miocene pelites and the argillaceous marl – silt facies sections of the flysch beds, as well as the Pannonian clay-bearing beds can be regarded the same way.

Trapping

The top zone of the formations older than the Upper Cretaceous can be a possible stratigraphic trap regarding the stratigraphic and tectonic features of the area. Reservoirs in the Pannonian sandstones can be associated with structural closures.

Each of the hydrocarbon occurrences on the Hajdúnánás High is associated with structural capping. The gas fields of the Újfalu Formation, and the traps of the Middle Miocene volcanics belong to this type.

The hydrocarbon occurrences of the Nyírség

Data characterising the discovered reservoirs (hydrocarbon composition, calorific value, etc.) basically are originated from the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ), in other cases the source is indicated.

Hajdúnánás–IV. The HHEN–Hajdúnánás–1, –2, –5 wells drilled between 2008 and 2009 found low (0.2–0.4%) carbon-dioxide (CO_2) and (3–4%) nitrogen gas (N_2) containing natural gas with an average calorific value of 38 MJ/m^3 in 3 free gas reservoirs in Pannonian clay with silt and sandstone intercalations, and an oil reservoir with gas cap in Miocene fractured volcanics. The so-called Pegazus sand related to a structural trap and showing the main seismic amplitude anomaly is a 15–19 m thick, unconsolidated, upward-coarsening sandy reservoir of Pannonian age, saturated with gas in the depth range of 925 –1,009 metres bsl. The methane (CH_4) content of the gas is 86%, the C_{5+} content is 48 g/m^3. The Pann-L and Pann-M reservoirs discovered underneath in a thickness of 10 m and merely 4 m, respectively, contain similar composition gas.

In the fractured volcanic reservoir 30–47 m^3/day oil was produced after a longer trial production period in the HHEN–Hajdúnánás–1 well. No oil-water contact (OWC) was identified for the reservoir. The structural trap is situated in a measured depth of 961–965 m bsl. The recoverable hydrocarbons are related with the secondary porosity of the reservoir (fractures), thus the porosity of the reservoir is low, it was determined as 1%. The density of the intermediate type oil is 753 kg/m^3. The calorific value of the gas is 37.9 MJ/m^3, its methane content is 88%, the CO_2 and N_2 contents are 0.05% and 1.1%, C_{5+} 43 g/m^3.

HHEN–Görbeháza–1 and –5 wells exploring the south-western side of the structure bearing the occurrence the latter proved dry. The HHENy–Görbeháza–1 well however identified two additional small sized Pannonian reservoirs (named Pann-F and Pann-H). Free gas with condensate were accumulated in the structural traps between 880–884 metres and 926–929 metres bsl, respectively. The methane content of the gas is 84–86%, CO_2 content 0.4%, N_2 content 3–4%. The condensate content is 18–68 g/m^3.

The occurrence is situated directly along a dextral lateral fault, separating the source rocks and the reservoirs, thus primary migration could have taken place along these faults, and along the unconformity surface of the volcanics. Each of the reservoirs on the Hajdúnánás High is attached to faulted closure. Based on 2016 data the hydrocarbon reserves of the Hajdúnánás occurrence was produced.

Hajdúnánás–V. The three-way closure trap was identified by seismic measurements in the 2005–2014 period (Chevelle or Tiszavasvári structure). The *L sandstone*, the *Pannonian_Q sandstone*, *M sandstone and N sandstone* reservoirs were discovered by the Hn–1, –2, and Tiv–6 wells in the beds of Pannonian sandstones overlying each other. According to the models the structure is a part of an active hydrocarbon system, its filling can be clearly derived from the Tiszapalkonya depression. The hundreds of metres thick Lower Pannonian free gas containing layers drilled by the Tiv–6 well are able to fill up the sandstones of the younger Pannonian reservoir directly.

Tiszavasvári South (Tiszavasvári-Dél–IV). The HHEN–Tiv–6 well was drilled at the edge of the Tiszapalkonya depression — known as the northern continuation of the Jászság Basin —, and exposed natural gas in low permeability Miocene tight sandstone beds which can be extracted by unconventional methods (Járai et al. 2012a).

Other indications

The Nagyecsed (Necs)–1 geophysical key well was drilled in 1973 and combustible gas was indicated at a depth of 3,059–3,072.5 m and 3,113–3,123 m in fractured andesite.

The sandstone layers of the Tiszaberek–I well drilled in 1934 accumulate water with gas traces below 920 m, and according to the formation tests carried out in the 1990s 94% of the observed gas was methane. At 947–950 m bitumen traces were detected.

After finishing a small-scale seismic survey carried out in the Tiszakeszi and Kömlő region, in the second half of the 1990s the Tiszakeszi–1 well was drilled. Gas traces were found during the drilling of the 2,144 m deep well in the volcanic Miocene beds appearing at 2,069 metres, but no water supply was detected during the formation tests. The Miocene layers in the surrounding Újszentmargita (Uma)–1 and –2 wells also proved impermeable.

In the Fehérgyarmat–2 well completed in 2006 the targeted Upper Pannonian conglomerate layers contained only very little dissolved gas containing groundwater, but at the base of the Lower Pannonian succession, between 1,044 and 1,093 metres gas indications were observed. Indications are assumed to have been migrated from Lower Pannonian layers of the deeper Mátészalka Basin into a higher structural position. Biogenic origin can also be assumed as an additional possibility of generation, the basis of which is provided by coal strips settled in Lower Pannonian layers (WÓRUM et al. 2010a).

The 2,794 metres deep HHEN–Tit–1 well completed in 2008–2009 was drilled to explore a small scale Miocene volcanic cone holding magnetic anomaly and identified at the Polgár 3D seismic data system as well, and the dome settled above it (Pooka prospect). The well revealed beds consisting predominantly of clay and silt layers without sandstones in a depth between 1,700 and 2,400 metres with a seismic facies containing only weak reflections in the Lower Pannonian sequence, without gas indications. The Miocene succession were reached by the well at a depth of 2,435 m, in the top zone of which a sequence consisting of alternating layers of thin limestone / calcareous marl, tuff and argillaceous marl layers was drilled. The tuff content becomes more and more dominant downward. At 2,458 m significant gas indications were found which also contained C_{5+} components, referring to wet gas / oil. The high background gas values lasted up to the bottom of the well. From a depth of 2,555 metres up to the bottom the well found effusive volcanic rocks (lava) and tuff, providing clear evidence that the drilling hit a strato-volcano. The drill and formation tests results suggest that the Tit–1 well identified a highly water saturated reservoir with poor permeability and with oil traces at a depth of 2,555 m and 2,563 m.

Occurrences in the surrounding, across the border

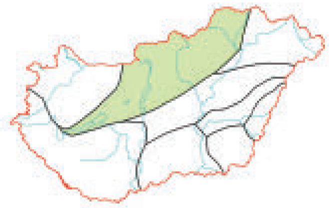
In Slovakia, to the east from Kosice a basin filled up with thick Miocene sediments can be found, which is probably connected to the Nyírség. Significant reservoirs were identified here in Karpatian and younger sediments. According to the paleo-geographic reconstruction accepted these days the connection between the area and the hydrocarbon bearing Eastern Slovakian Nagymihályi Basin during the Middle Miocene cannot be excluded.

In Ukraine, near Korolevo (Királyháza) two wells explored combustible gas in Pannonian sandstone (between 710 and 740 m), but also close Vynohradiv (Nagyszőlős)–005 well proved dry for hydrocarbons. Somewhat further up, in the Munkács (Mukacevo) Basin, Sarmatian sediments and pyroclasts of the Inner Zakarpatia Neogene depression store combustible gas, while beside Szolyva the Upper Cretaceous silts and sandstones provide combustible gas.

Intensive research is being carried out in the area near the Romanian national border at the Szatmárnémeti (Satu Mare) concession area, which is currently one of the largest exploration zones in Romania. Exploration of the Berkeni (Börvely) area was also started in 2014 using the analogy of the multiple reservoir Moftinu (Nagymajtény) natural gas field accumulated in structural traps and discovered on the basis of seismic amplitude anomalies in the low depth Pannonian formations.

Hydrocarbon exploration areas in Hungary — The Hungarian Palaeogene Basin

Edit Babinszki, Zsolt Kercsmár, Zsolt Kovács



4.9

Exploration history

In the Hungarian Palaeogene Basin (HPB) the first well discovering natural gas was deepened in the Őrszentmiklós–Vicián ranch in 1911; it was drilled without any geological preparations, in order to produce water. The well produced salty water from a depth of 230 metres, followed by natural gas blowout. Additional wells drilled in 1913–1914 and later in 1935–1936 also found natural gas. The exploration of the area by shallow boreholes took place in 1954–1955.

The wells — which explored the anomalies of the gravity measurements of the time — were drilled in the vicinity of Budapest, Gödöllő and Monor in the 1950s (Gödöllő, Tura, Tóalmás, Cinkota, Mátyásföld, Rákos, Őrszentmiklós). Some of these wells discovered combustible gas, which, however, were of non-commercial quantity, and of biogenic origin.

In the foreland of the Bükk Mountains the Geological Institute of Hungary carried out surface geological mapping in 1932–1934, and the Eötvös Loránd Geophysical Institute of Hungary (MÁELGI) made gravity measurements in 1933. Hydrocarbon explorations were started in the southern foreland of the Bükk in the 1940s, and in several places in the 1950s (Dank 1983). The occurrences (Bükkszék, Fedémes) and indication (Recsk) of the accumulation belt in the Darnó Zone, identified in the 1930–1950s, are unambiguously associated with the Darnó Line as a tectonic (reverse fault) structure. The Bükkszék occurrence was found in 1937; however, oil traces had been known in the area since 1880. The Mezőkeresztes oil field was discovered in 1951. The Demjén oil field can be found in the northern rim of the Vatta–Maklár Trough; its exploration started in 1953–54. This was followed by the identification of the satellite oil accumulations of the Demjén field. Slight oil and gas traces were detected in several exploration areas in the wells of Emőd, Tard and Sajóhidvég.

The first gravity measurements were made by MÁELGI (Eötvös Loránd Geophysical Institute of Hungary) in the 1950–60s around Ózd, along the accessible roads. New measurements in a regular grid were prepared only in 1992–1993. The first magnetic measurements were also made by MÁELGI in the 1950s, using conventional field balances. The Szécsény, later the Sóshartyán inert gas occurrences were found in 1966 and 1971, respectively.

The Tura–1 exploration well was drilled in 1954 and explored oil traces. At the end of the 1950s and at the beginning of the 1960s the Tura–2, –3, –4 and the Tóalmás–1, –2, –3 wells were drilled, which tested only non-commercial hydrocarbon shows.

In the vicinity of Jászberény MÁELGI carried out exploration gravity measurements already in 1937. Eötvös torsion balance measurements were completed in some parts of the area in different periods between 1938 and 1955 in several steps. After 1956 gravity measurements took place along the accessible roads, but detailed measurements were carried out only in 1979–1981 and between 1979–1982 in the Heves area and in Jászjákóhalma, respectively. Geomagnetic measurements in the area were carried out by MÁELGI in the 1950s. Between 1979–1982, the same time when the gravity measurements were made, more detailed magnetometric measurements were also completed in Jászjákóhalma and Heves.

The Bugyi Bu–1, –2 and the Jászberény Jb–1, –2 wells were drilled in 1947–48 and 1952–53, respectively. The one marked Jb–1 produced oil and gas shows. The continuation of the exploration by drilling needed seismic reflection measurements, which were carried out by GKÜ (Geophysical Exploration Co. of the Hungarian National Oil and Gas Trust [OKGT]) between 1953 and 1966. The Mezőkövesd Mk–3 well was drilled on the north-eastern limb of the detected Mezőkövesd structure. The Farmos–1, –2, …, –6 wells were deepened on the indication found at Farmos from 1963 on, exploring non-combustible and combustible mixed gas accumulations.

Between 1969 and 1976 seismic measurements were completed in the surroundings of Demjén–Füzesabony–Heves–Jászapáti–Jászkisér. Around Jászberény two pilot wells were drilled to gain information: in 1972 the one marked Tarnabod Tarna–1 up to a depth of 3,101.5 metres and in 1974 Kömlő–1 to a depth of the 4,000 metres. Seismic measurements took place in the area in several stages from 1970 on. Mol Hungarian Oil and Gas Plc acquired 2D and 3D seismic and magnetotelluric measurements in the area in the 2002–2012 period, and drilled the 3,030 metres deep Jászberény Jb-ÉK–1 well, which proved dry.

Around Tura the seismic survey and the drilling exploration based on it started only in the 1980s. In the anticline structure detected on the basis of the seismic surveys carried out on the Tura gravity anomaly in 1987 crude oil occurrence with gas cap were found. In 1989–1990 region-wide, general seismic reflection measurements were completed in the area.

Between 1989 and 1995 exploration activity was conducted in the Tura, Mogyoród and Dány regions. The Tura–5, –6 wells drilled at this time discovered oil and combustible gas, whereas the Tura–7, –8 wells oil reservoirs in some places with gas cap. The Dány–1 well in 1994 was deepened on the most favourable point of an anticline structure measured with seismic method. The well explored the most significant hydrocarbon occurrence of the area up to that date. 3D seismic acquisition completed in 1995 at Isaszeg, Dány and Mende. The Isaszeg–1 well drilled at this time proved dry. The SW part of the Palaeogene Basin was explored by the Mol Plc at that time (Szalainé et al. 1997). However, the further well (i.e. Dány–2), drilled south-east of Dány–1 which identified the oil occurrence, proved dry in the pre-Oligocene layers. The Monor-É–1 well and the Mogyoród-É–1 well discovered oil and natural gas reservoirs in 1997 (Kiss et al. 1999).

In the Emőd North area, which is located in the south-eastern foreland of the Bükk, and where the Mezőkeresztes hydrocarbon accumulations can be found, exploration of the Mol Hungarian Oil and Gas Company Plc was finished in 1996 (Hajdú et al. 1997), without suitable hydrocarbon discovery.

Exploration of the Occidental Oil and Gas Corporation of Hungary Inc have been concluded in the Heves–I concession areas (southern foreland of the Bükk Mountains – Vatta-Maklár Trough), adjacent to the Emőd North and the Görbeháza exploration area in 1997. After the seismic measurements the company did not drill wells.

New exploration period was started by the Mol Plc in 1999 at the Gödöllő exploration area; 4 oil and 2 gas condensate reservoirs were identified by measuring 194 km 2D and 912.1 km^2 3D seismic data and drilling 17 exploration wells, respectively. Next, the most recent efforts started in the vicinity of Monor in 2004, when 7 oil reservoirs were discovered by 16 exploration wells on the base of the interpretation of 252 km 2D and 484 km^2 3D seismic data. In the Gödöllő and Monor areas exploration of the Mol Plc resulted the discovery of the oil (Tóalmás–I, Tóalmás–III), free gas and gas condensate reservoirs (Tóalmás–II, Szentmártonkáta) of the Tóalmás South field, the Nagykáta oil reservoir in the period between 1999 and 2002 (Holoda, Szilágyi 2004b, c), the Gomba field in 2003–2005 (Boncz et al. 2004, Holoda, Szilágyi 2004a), and the Sülysáp North oil occurence in 2008 (Boncz et al. 2013b).

Mature source rocks younger than the Late Cretaceous was confirmed by the Baracska–1 well at the Martonvásár exploration area (Boncz et al. 2001) situated in the Transdanubian part of the Palaeogene Basin.

In the Sárbogárd, Mezőfalva and Csepel South area to the south of Budapest the purpose of the exploration was to enlarge information about the tectonic, stratigraphic, hydrocarbon geological characteristics of the area, and to explore reservoirs in the Mesozoic, pre-Neogene and Neogene successions. The existing seismic profiles were re-interpreted and more than 200 km new acquisition was made; as a result of the exploration hydrocarbon indications were found (Sőreg et al. 2002a). In the prospective Csepel exploration area the Tököl–1 well did not discover any substantial hydrocarbon accumulation (Sőreg et al. 2002b).

In the Salgótarján area (Kósa et al. 2003) the main objectives of the research were to further develop of the geological, hydrocarbon-geological model of the Zagyva Trough, the seismic interpretation of the potential reservoir horizons and the appointment of potential prospects for drilling under the Miocene volcanics.

In the Encs area (Bodrogi et al. 2003) the exploration programme included the enlargement of the hydrocarbon-geological knowledge and identification of Neogene, pre-Neogene prospects. In the course of the work 108 km 2D seismic line was measured. No objects with sufficient hydrocarbon exploration potential could be identified in the project, therefore no drills were deepened.

In the Ercsi area, in the Transdanubian part of the Hungarian Palaeogene Basin (Boncz et al. 2013a) the purpose was the exploration of the deep structures located close to the hydrocarbon generating source rocks. In the course of the research 183 km^2 3D, and 25.5 km 2D seismic measurements were carried out, and two wells were drilled. The Ráckeve–1 well drilled to explore the Ráckeve Mesozoic structure and it confirmed the geological model, but proved dry. The Ráckeve-Ny–1 well was drilled into a Miocene domed structure, but proved dry just as well.

In the Jászberény exploration area (Boncz et al. 2012a) the purposes included magnetotelluric, 221 km^2 3D, and 274 km 2D seismic measurements, and one well was drilled. The purpose of the Jászberény-ÉK–1 well was exploring the Eocene succession and the pre-Cenozoic basement structure detected NE of Jászberény town. The well justified the expected geological model but no commercial hydrocarbon accumulation was observed.

Exploration works in the Bátonyterenye area, north-eastern Hungary (Boncz et al. 2012b) aimed the determination of the extension of the Palaeogene sediments, identification of potential objects under the Miocene volcanics, and mapping potential reservoir horizons. The work programme involved 265 km 2D seismic measurements and two wells were drilled, the Hatvan-É–1 (total depth: 2300 m), and the Bér–1 (1400 m TD). The Hatvan-É–1 well was deepened in order to explore the interpreted Hatvan North prospect. Mesozoic sequences were assumed under the thin Pannonian sequence and the thick Miocene volcanics, but expectations could not be confirmed. The Miocene was much thicker than expected and the Upper Oligocene sandstone underneath could have not been penetrated by the drilling. The Bér–1 well prooved also dry.

Exploration well test results and the discovered hydrocarbon occurrences in the Monor exploration area (Boncz et al. 2013b) confirmed the favourable hydrocarbon genetics, migration and trapping conditions.

In the course of the studying of the Hernád–I area in 2005–2014 carried out by the MHE Magyar Horizont Energia Kft. (HHE Hungarian Horizon Energy Ltd) remaining available hydrocarbon potential of the Mezőkeresztes area was explored

by the integration of geophysical data and new geological information measured since the abandonment of the Mezőkeresztes field, and by the re-interpretation of the former data, the Mezőkeresztes NE structure was idientified, which is a potential hydrocarbon prospect according to the findings (TÓTH, WÓRUM 2015).

Geological overview

The pre-Tertiary basement of the Hungarian Palaeogene Basin (HPB) is made up of the so-called Alcapa Unit of complex structure, which is bordered by four main structural elements, i.e. the Rába Line, the Balaton Line, the Darnó Zone, the Diósjenő–Ógyalla Line and the Hernád Line, intersecting it at the same time into structural units. The Balaton Line — bordering the basin from the SE, the Darnó Zone running into the latter from the NE and the Diósjenő Line running along the northern part of the basin together encompass the Transdanubian Range Unit, which is accompanied by the Vepor, the Gemer and the Aggtelek–Rudabánya Units in the north, by the Bükk Unit in the east, and by the Mid-Transdanubian Unit in the south. The NE part of the Balaton Line and the sharp turn in the course of the Hernád Valley branching off towards the north–north-east separate the Tisza Mega-unit from the Bükk, the Szendrő–Uppony, and the Aggtelek–Rudabánya nappe units. In the west the Szendrő–Uppony Unit is separated from the Aggtelek–Rudabánya Unit by the reverse faults of the Darnó Zone.

Geological formations of the HPB were deposited in the area of the structural units of the Transdanubia and the Bükk, from the Keszthely Mountains up to the eastern foreland of the Bükk Mountains delineated by the Hernád fault, and inthe Vepor, Gemer and Aggtelek–Rudabánya Units, covering the Ógyalla–Diósjenő Line. One of the important structural elements of the Palaeogene sedimentary basin which can be modelled by a flexural basin structure (TARI et al. 1993) which can be defined in terms of sedimentary geology is a structure of NE–SW strike recognised as blind reversed fault (blind thrust, “Buda Line”) (FODOR et al. 1994), which was a significant facies boundary in the Late Eocene – Oligocene. Beside this, the HPB is characterised by synsedimentary right lateral strike-slip faults with WNW–ENE strike created by NW–SE, and WNW-ENE compression, and the extension stress field perpendicular to it, as well as by left lateral strike-slip faults with a significant normal component with NW–SE strike. In certain areas (northern part of the Vértes Hills, southern part of the Gerecse Mountains) reverse faults with south-eastern vergence (FODOR, BÍRÓ 2004) and NE–SW strike rifts most probably belonging to flexural extension which are perpendicular to the compression directions (KERCSMÁR 2004, 2005) appear along the structures inherited from the Late Cretaceous at the beginning of the Palaeogene. These may be accompanied by smaller normal faults and rifts encompassing Neptunian dykes The characteristic feature of the flexural basin structure development is the facies migration from NW to SE and the depocentre migration growing younger from SW to NE, which is substantiated by more and more data. At the same time large scale horizontal fault creating the hypothetical basin form (backthrust) to the north-west from the range of the Transdanubian Mountains (around the Rába tectonic line) is still unknown. In the absence of it, it can be assumed that certain basins within the HPB must be interpreted as low amplitude folds (FODOR 2010).

The HPB moved to its present geographic position in the syn-rift phase of the structural evolution of the Carpathian Basin, when main tectonic lines separated the structural units operated as significant lateral displacements. Deep trans-tensional pull-apart basins came into being along the tectonic lines; as a result of this, the Palaeogene formations were buried into great depths in certain places which favours hydrocarbon generation, and were sheared in the wrench zones. As a consequence, reverse fault structures were also formed in the transpression zones of the displacements (CSONTOS, NAGYMAROSY 1998). Later the main tectonic lines were renewed (even with opposite nature just as well), resulting in further fragmentation of the basin sediments, favouring further development of the structural type hydrocarbon traps.

Basement rocks

The complex basement of the HPB is made up of significantly different carbonate, clastic, igneous and metamorphic formations characteristic of the tectonic units.

In the middle and south-western parts of the basin the Palaeozoic succession of the pre-Cenozoic basement is built up of the Carboniferous and Permian carbonate and coarse clastic succession folded up into a syncline, which is typical for the Transdanubian Range Unit, corresponding to the uppermost member of the Upper Austroalpine Nappe System. Palaeozoic rocks are penetrated by Carboniferous granitoid intrusion in the surroundings of the Velence Hills. Above them Triassic formations characterised by shallow-marine carbonate sequences of the carbonate platform and marly, argillaceous marly formations of intraplatform basins, as well as volcanic tuffs, and Jurassic formations of rifting, bathyal deep basins dissected by submarine highs, finally Cretaceous formations represented by flexural basin evolution, locally by denudation, in other places by shallow-marine carbonates of reef facies and deep-water marly layers, and turbidite-like sediments are typical for the Mesozoic succession.

In the NE part (Figure 4.9.1) the very low-grade metamorphic Mesozoic formations — overlying the Gömör–Veporian crystalline Palaeozoic and Permian – Lower Triassic anhydrite layers of the Bükk Mountains, the Aggtelek–Rudabánya and the Gemer structural units — are characterised by the rapid dissection of the carbonate platforms, calc-alkaline and neutral

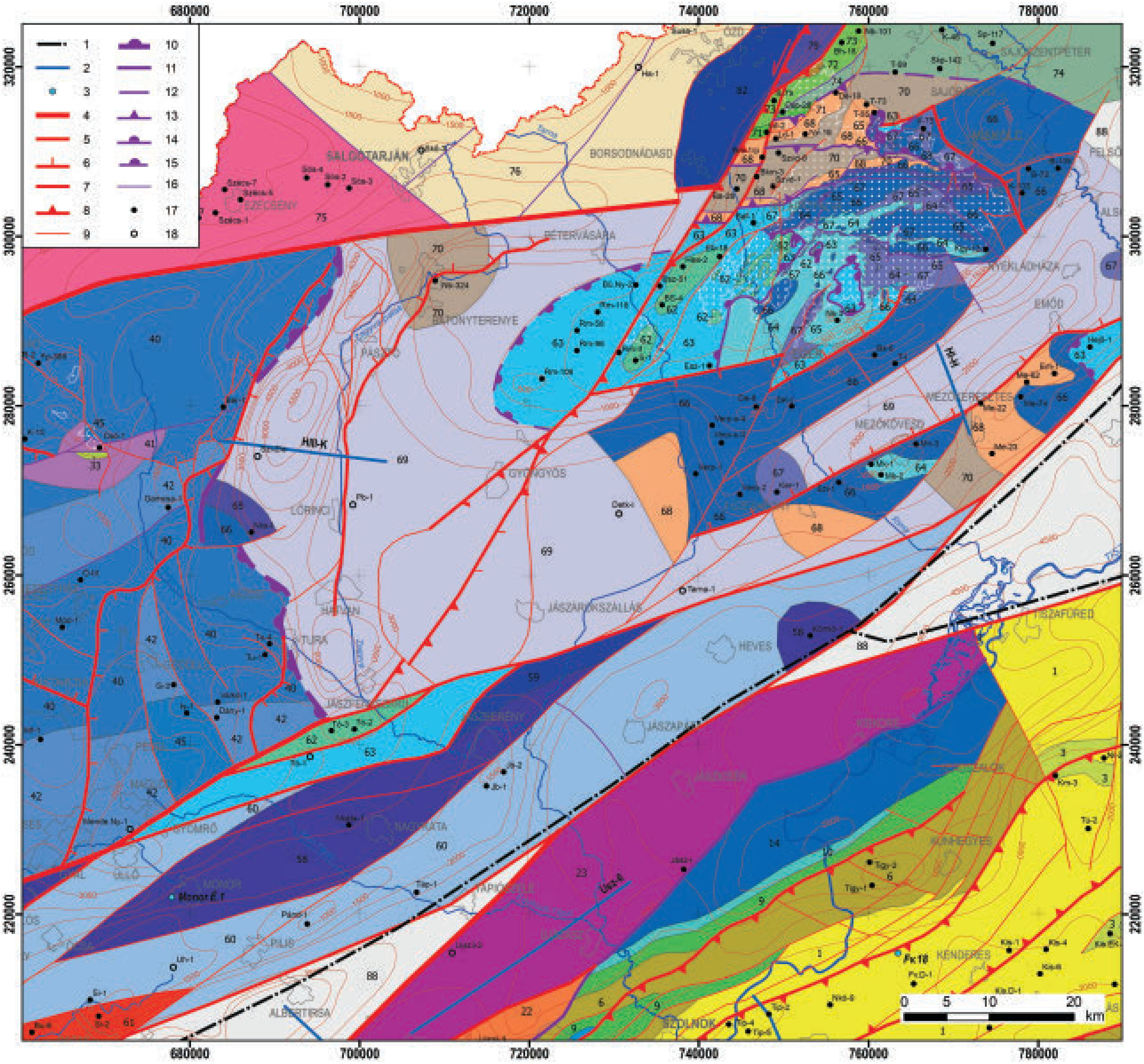


Figure 4.9.1. Pre-Cenozoic geological map of the north-eastern part of the Hungarian Paleogene Basin (HAAS et al. 2010)

Elements of legend: 1. boundary line of the sub-basins, 2. trace lines of the sample 2D seismic profiles in this chapter, 3. Location of well including sample geophysical logs on the figure in this chapter, 4. first-order Cenozoic tectonic line, 5. second-order Cenozoic tectonic line, 6. second-order Cenozoic normal fault, 7. second-order Cenozoic tectonic line, 8. second-order Cenozoic reverse fault, 9. third-order Cenozoic tectonic line, 10. first-order hypothetical Mesozoic nappe, 11. second-order Mesozoic tectonic line, 12. second-order hypothetical Mesozoic tectonic line, 13. second-order Mesozoic reverse fault, 14. second-order Mesozoic nappe, 15. second-order hypothetical Mesozoic nappe, 16. third-order Mesozoic tectonic line, 17. well hit the pre-Cenozoic basement, 18. well stopped above the pre-Cenozoic basement

Legend for geological formations: 1. Senonian–Palaeogene pelagic marl, flysch, 3. Senonian continental, shallow- and deep-marine formations, 6. Lower Cretaceous basic volcanics and their reworked marine sediments, 9. Middle Jurassic - Lower Cretaceous pelagic limestones, cherty limestone, 10. Lower–Middle Jurassic pelagic fine-grained siliciclastic formations, 13. Middle Triassic shallow-marine siliciclastic and carbonate formation, 14. Lower Triassic siliciclastic formation of fluvial and delta facies, 22. Variscan granitoid rocks, 23. Variscan metamorphic complex (gneiss, mica, amphibolite), 33. Senonian basinal limestones and marls, 40. Upper Triassic–lowermost Jurassic platform limestones, 41. Norian–Rhaetian and lowermost Jurassic basinal cherty limestones, dolomites, 42. Carnian–Norian platform dolomites, 45. Ladinian–Carnian platform dolomites, 58. Middle–Upper Triassic carbonate formations of platform and basin facies, 59. Lower Triassic shallow-marine claystones, marls, limestones, 60. Upper Palaeozoic and Mesozoic formations in general, 61. Permian shallow-marine siliciclastic and carbonate formations, 62. Jurassic basic magmatites, 63. Middle Jurassic olistostrome melange, 64. Very low-grade metamorphic Middle–Upper Jurassic pelagic succession (radiolarite, shale), 65. Middle–Upper Triassic metavolcanics, 66. Low-grade metamorphic Middle and Upper Triassic platform carbonates, 67. Very low-grade metamorphic Middle–Upper Triassic cherty limestones of toe-of-slope and basin facies, 68. Very low-grade metamorphic Upper Permian - Lower Triassic shallow-marine limestones, sandstones, marl, 69. Very low-grade metamorphic Upper Palaeozoic and Mesozoic formations in general, 70. Very low-grade metamorphic Upper Palaeozoic marine formations, 71. Senonian marine conglomerate, 72. Low-grade metamorphic Devonian–Carboniferous platform carbonates, 73. low-grade metamorphic Devonian–Carboniferous basinal carbonates, 74. Low-grade metamorphic Carboniferous basinal siliciclastic formations, 75. Medium-grade polymetamorphic complex (gneiss, mica, amphibolite, greenschist, phyllonite), 76. Palaeozoic and Mesozoic formations in general, 79. Middle Triassic - Carnian shallow-marine carbonates, 82. Lower Triassic shallow-marine sandstones, marls, limestones, 88. inadequately evaluable or unknown basement

volcanism, deep basin, shelf-slope and reef facies, as well as mid-ocean ridge volcanism (ophiolite) and Jurassic olistostromes are the most typical in the frequently overturned sequences.

The basement of the Szendrő–Uppony Unit is built up of slightly metamorphosed carbonates of Devonian–Carboniferous age and Cretaceous marine conglomerate.

Basin fill sediments

After the Late Cretaceous – Early Eocene denudation period sedimentation characterised by a shift of the facies from SW to NE in space and time and by erosional gaps decreasing from NW to SE as a result of the Palaeogene flexural basin development (Tari et al. 1993) from the very beginning of the Middle Eocene up to the lowermost Ottnangian of the Miocene (Figure 4.9.2). From the very beginning of the Middle Eocene up to the middle of the Late Eocene lagoonal and near-shore calcareous, marly, sandy, and continental alluvial (Dorog and Csernye Formations), whereas later in a ramp environment carbonate sedimentation took place (Szőc Limestone Formation) in the margins of the south-westward deepening basin. In the basins, at the same time, the deposition of fine-grained silt, upwards fine argillaceous marl formations (Csolnok Clay Marl Formation) — heteropic with the carbonate ramp — took place, in the upper part of which a succession, indicating significant siliciclastic influx, can be found (Tokod Formation). The beginning of the deposition of

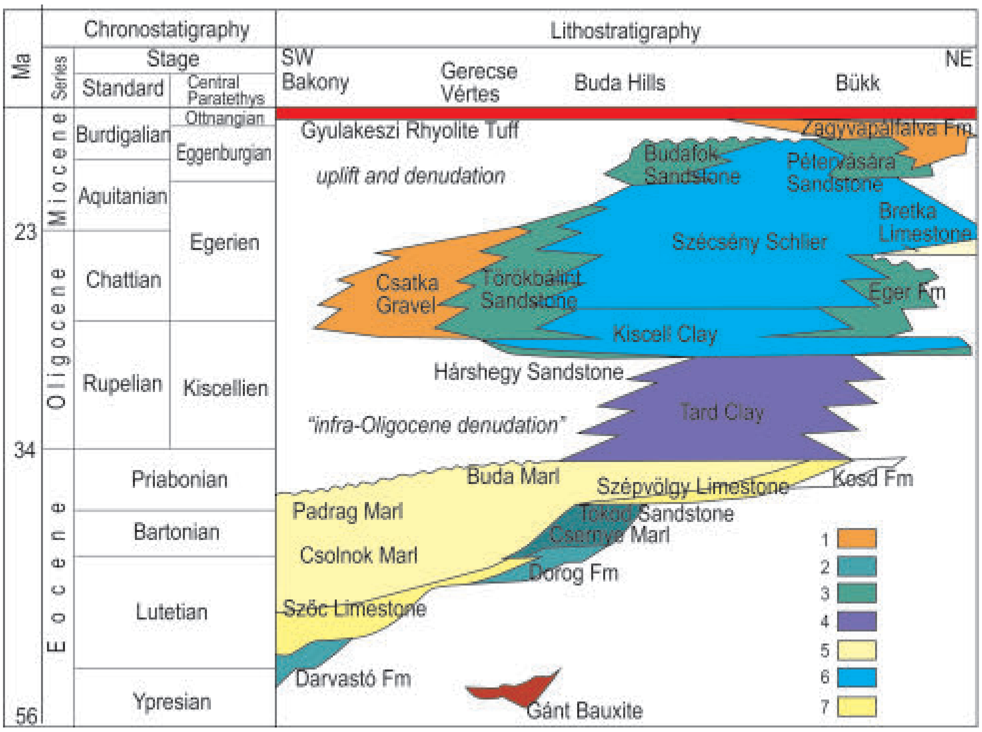


Figure 4.9.2. Lithostratigraphic and faciological correlations of the Palaeogene sedimentary cycle in the Hungarian Palaeogene Basin (adapted from Tari et al. 1993)

Legend: 1. continental sand, clay, 2. coal seams, 3. shallow-marine sand/sandstone, 4. euxinic clay, 5. bathyal marl with turbidites, 6. bathyal siltstone, 7. shallow-marine limestone

marine sediments was shifted from SW to NE getting gradually younger, in space up to the "Buda Line" of NE–SW strike, and in time up to the beginning of the Late Eocene. The Buda Line is seen as a significant facies boundary in the Palaeogene. As a result of a new sedimentary cycle another carbonate ramp (Szépvölgy Limestone Formation) was built up from the Late Eocene onward covered the Buda Line and prograded to the east and to the west from it. The north-western relations of the Upper Eocene carbonate ramp are uncertain due to the denudation of the Eocene formations; however, to the south-east of the area the carbonate layers are heteropic with the basin marl formations (Buda Marl Formation) which subsided to a great depth within a very short period of time, and where they are present as carbonate turbidite and occasionally olistolithes. Simultaneously with the subsidence of the south-eastern foreland, which started in the Late Eocene, the foreland located to the north-east of the Buda Line should have been uplifted, which resulted mostly in the heavy denudation of the Eocene formations in the Oligocene. For the Late Eocene the deep basin environment was shifted to the eastern part of the HPB, where continuous sedimentation took place up to the Early Miocene.

In the North Hungarian Range and its forelands carbonate sedimentation took place first in the Late Eocene, overlying the breccia and conglomerate interbeddings in the locally thick red clay and clayey sand layers.The carbonate succession is conformably overlain by the formerly mentioned basinal marl, calcareous marl layers. The deepwater marl has a continuous transition upwards into the Oligocene Tard Clay Formation representing the deepest facies of the HPB, and containing euxinic, shallow bathyal clay, clayey silt layers, which is the main source rock for hydrocarbon generation in the Palaeogene Basin. The Tard Clay Formation can be traced in a large areal extension to the ENE of the south-eastern part of the Velence

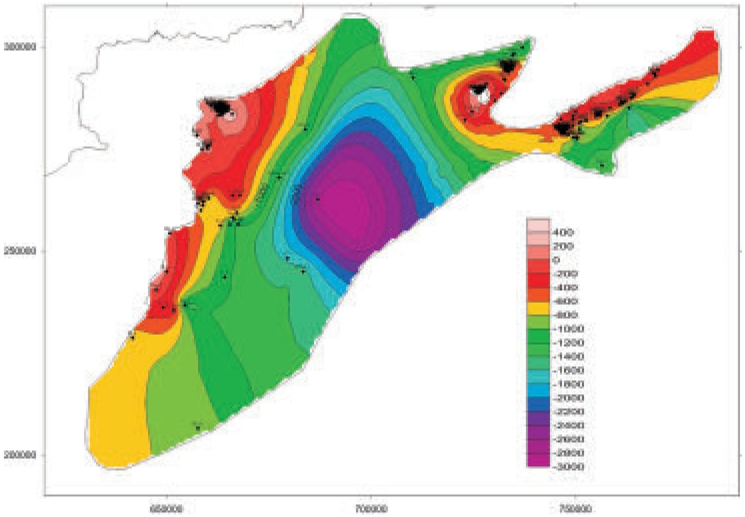


Figure 4.9.3. Depth map of the base Tard Clay Formation based on well data

Hills up to the eastern foreground of the present day Bükk Mountains. The south-eastern termination of the formation is marked by the south-eastern part of the Mid-Hungarian shear zone, the north-western border partly by the Buda Line, partly by the Diósjenő Line (however, the latter is partly covered by it). The greatest depth in which the formation occurs is in the Darnó Zone fracture belt (Figure 4.9.3). The greatest depth of the Tard Clay in the Vatta–Maklár Trough region was 2,500 m based on the seismic surveys (Heves–I exploration area, 2001–2003). Certain studies suggest a depth of 4,000 metres in certain parts of the basin just as well (Figure 4.9.3, 4.9.4). The formation reaches its maximum thickness in the Darnó Zone and its continuation towards the SW, in the small sub-basins along the Balaton Line (Valkó, Nagy-

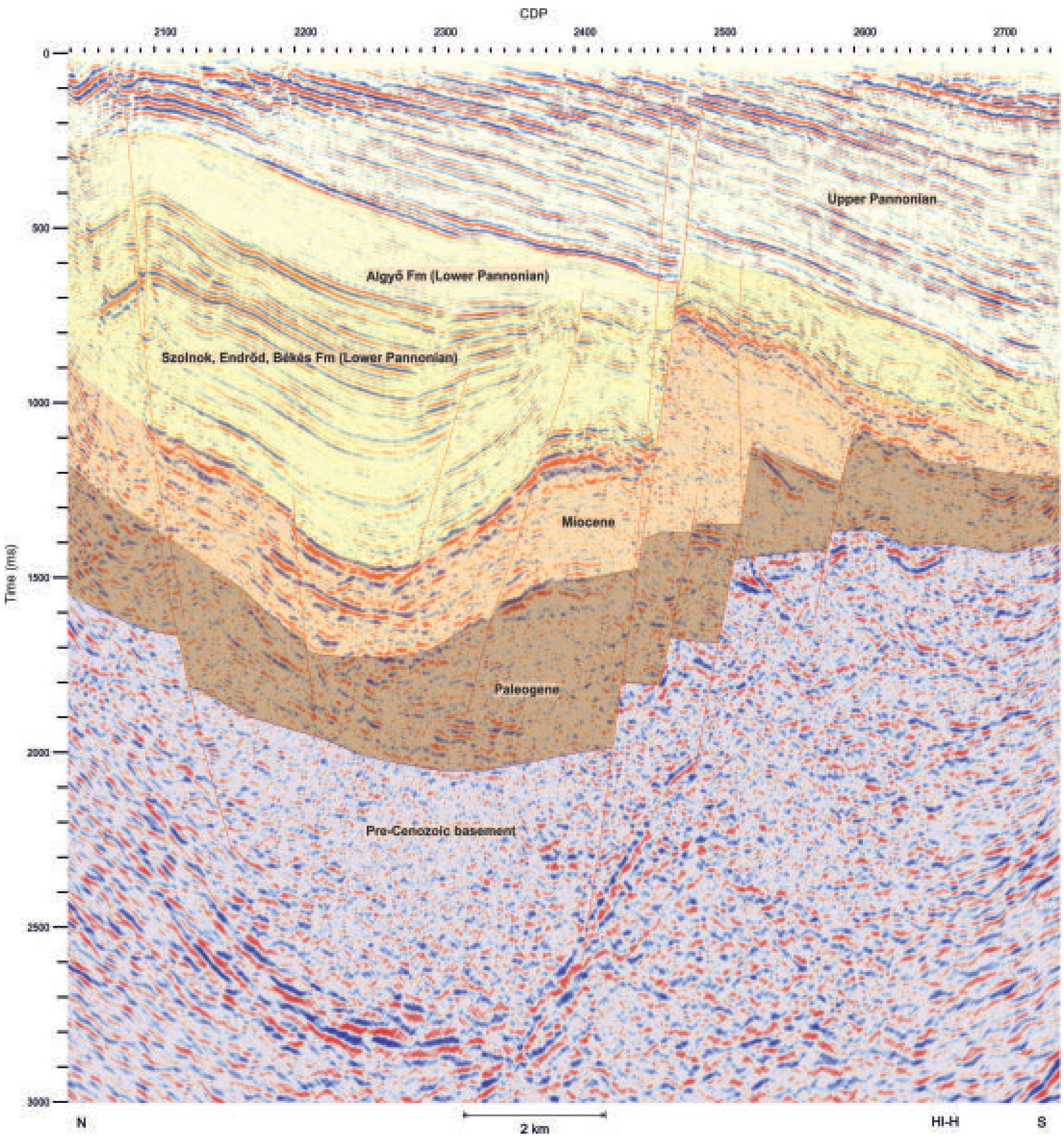


Figure 4.9.4. The HI-H seismic section crossing the Vatta–Maklár Trough (the trace line of the profile can be seen in Figure 4.9.1)

lózs), furthermore in the south-eastern foreland of the Bükk (Figure 4.9.5). All significant hydrocarbon accumulations derived from Palaeogene source rocks are connected to these structural deep zones.

Upwards there is a transition from the Tard Clay into a basinal clay succession belonging to the maximum flooding period of the sedimentary cycle; the latter contains open water sand bodies (Kiscell Clay Formation; Figure 4.9.2). The lenticular, pinching out sand bodies — frequently functioning as hydrocarbon traps — show turbiditic features. The formation is widespread in the east and can be traced up to the Gerecse Mountains in the west of the HPB where it interfingers with the sandy, gravelly, shallow-marine, littoral coarse clastic sediments (Hárshegy Sandstone Formation). The deep-water clay with sand intercalations has good hydrocarbon trapping properties; therefore, it can be recorded as a potential stratigraphic trap. The nearshore sandstones became strongly silicious in the Buda Line zone; therefore, their pore volume is in general low, their permeability is poor, which impairs trapping conditions in this formation substantially. The evolution of the Hungarian Palaeogene Basin was accompanied by andesite volcanism, the lava rocks of which appear in the surroundings of the Velence Hills, at the same time the lava and the tuff are embedded in the layers of the Tard Clay Formation in the Mátra Mountains, which are, thus, also considered as potential reservoir rocks.

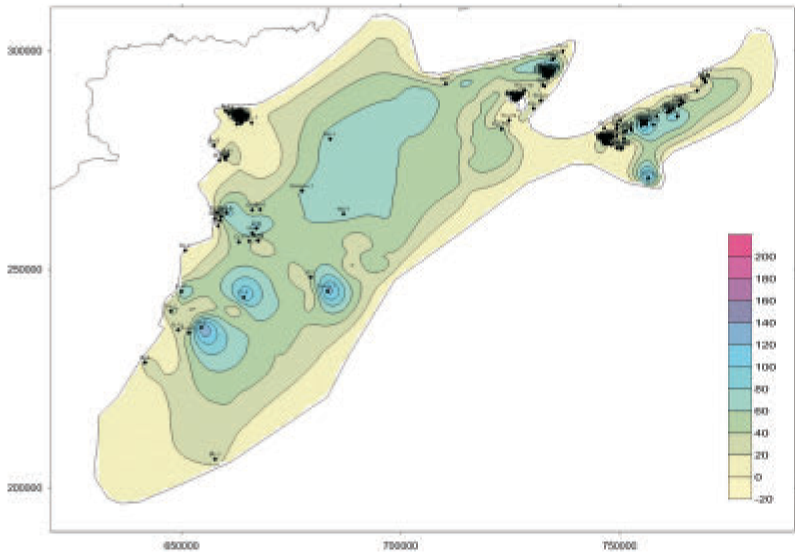


Figure 4.9.5. Thickness map of the Tard Clay Formation

As a result of the Late Oligocene regression cycle the clay-bearing formations in Transdanubia interfinger with the fluvial, continental gravel and sandy gravel, and silty sand, clayey sand and shallow-marine sand layers prograding towards the basin (Csatka and Törökbálint Formations). In the eastern areas of the HPB the fine-grained clastic, somewhat more calcareous sedimentation of basin facies (Szécsény Schlier Formation) continued. By the Early Miocene the basin became filled up with the sediments prograding from the east and from the west (Pétervására Sandstone Formation, Budafok Formation), and in the eastern hinterland lagoonal formations were developed (Salgótarján Brown Coal, Zagyvapálfalva and Felsőnyárád Formations). The sedimentary cycle finished with the deposition of the Gyulakeszi Rhyolite Tuff. In the younger period of the Miocene, i.e. during the Karpatian–Badenian sedimentary cycle, due to a rapid transgression, shoreline lagoonal sediments comprising sand and conglomerate layers and brown coal beds (Egyházasgerge Formation and Hidas Brown Coal Formation) were deposited on the eroded surface of the older Miocene formations. Subsequently, carbonates (i.e. the Badenian “Lajta Limestone” and the Sarmatian Tinnye Formation) were formed (which are more characteristic in the western areas). In the eastern area, above the thin carbonate and calcarenite layers, thick, deep-water, calcareous clay and schlier-like layers were deposited (Garáb Schlier), accompanied by effusive volcanic lava rocks, tuff layers, and volcano-sedimentary rocks derived from intensive volcanic activity (Hasznos, Mátra, Tar and Galgavölgy Formations).

This is shown by the HIII–K seismic section crossing the Zagyva Trough (Figure 4.9.6). Badenian volcanics of large areal extent may be good cap rocks for the hydrocarbons generated and trapped deeper (for instance in the surrounding of the Vatta–Maklár Trough), and in other eastern areas of the Palaeogene Basin. The Badenian age was an active period in the evolution of the Hernád fault, when the Badenian and Early Sarmatian sediments eastwards became interfingered with volcanic formations within a couple of kilometres. At the same time the rocks of the thick Tokaj Volcanic Formation — found in the eastern side of the Hernád fault — occur as intercalations in a thickness of some tens of metres on the western side of the fault.

The oldest Pannonian sequence in the HPB can be found in the north-eastern part of the area, in the northern forelands of the Aggtelek–Rudabánya Mountains and the Bükk, where clayey and lignite-bearing lacustrine sedimentation took place in the waterlogged, marshy, slowly subsiding area (Edelény Variegated Clay Formation). A large part of the sequence was denudated in the Late Pannonian. Pannonian sequences in the western and eastern parts of the area are characterised by coarse clastic sediments of alluvial plain and delta facies of rivers arriving from the NW and NE; this, for instance, can be studied in great thickness in the Vatta–Maklár Trough (Figure 4.9.6). In the area of certain elevated blocks (for instance the Vértes Mountain) Pannonian sand and gravel of littoral facies, as well as of abrasion littoral facies occur. In marshes developed in areas which were free from the coarse clastic sediments (North Hungarian Range, southern margin) lignite formation started. The HPB was subject to strong inversion during the Pliocene as well. According to certain concepts

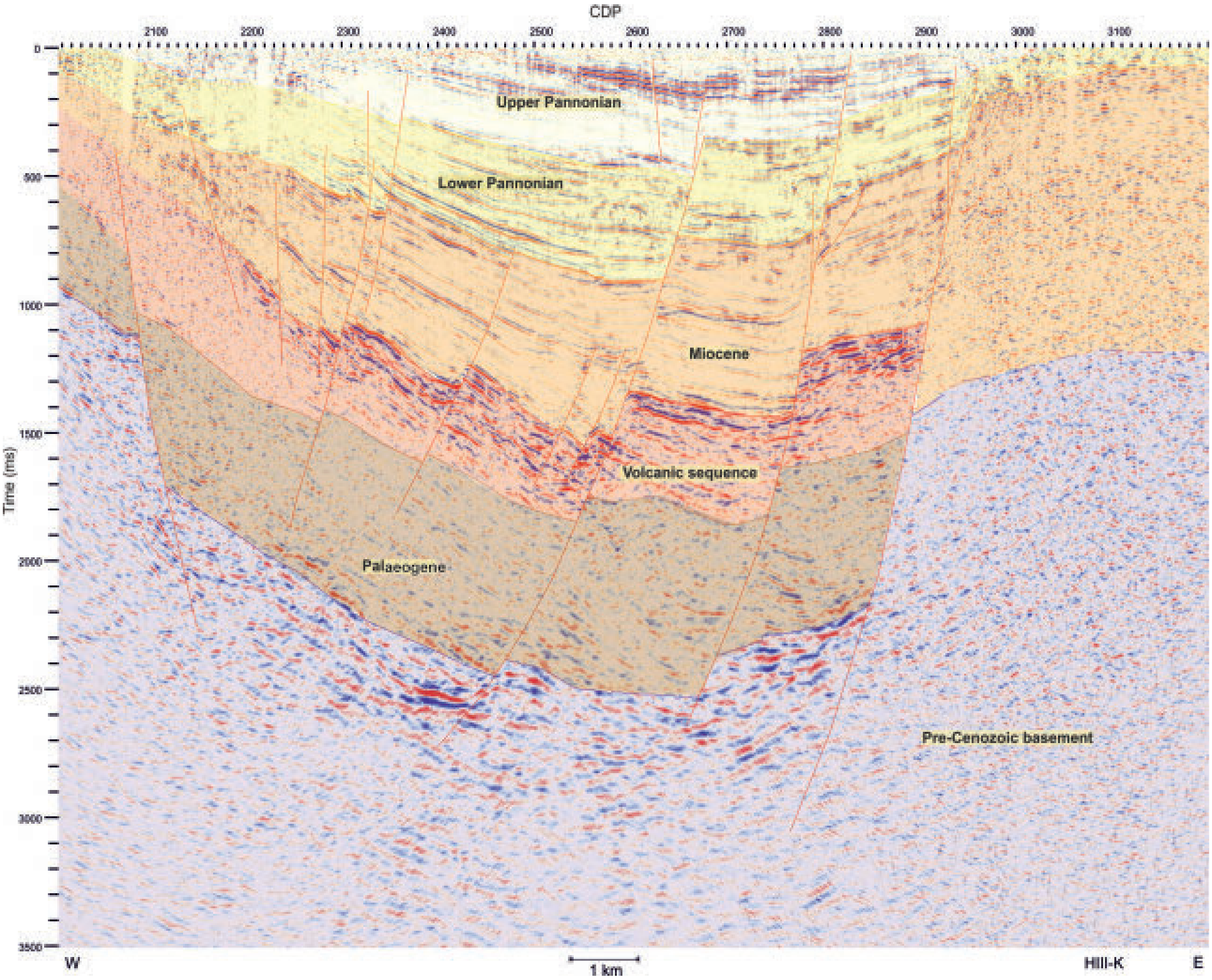


Figure 4.9.6. The HIII-K seismic section crossing the Zagyva Trough (the trace line of the profile can be seen in Figure 4.9.1.)

(SACCI et al. 1999) as much as 1,000 metre-thick sediment succession may be absent from the present surface of the Transdanubian Range.

The Quaternary sediments are represented in great thicknesses within the area of the Miocene transtensional basins, which underwent further subsidence in the course of the renewal of the main structural lines, mainly along the southern margins of the North Hungarian Range. In general, as a result of the uplifting of the mountains and the subsidence of the margins the piedmont areas are characterised by coarse clastic fluvial, proluvial and deluvial sediments, whereas the inner parts of the mountains and the valley fills by loess and aeolian sand layers, and the actively subsiding areas (for instance the Jászság Basin) by fluvial sedimentary sequences in great thicknesses.

The theoretic stratigraphic column of the area is shown in Figure 4.9.7.

An overview of hydrocarbon geology

Source rocks

Wells drilled source rocks of appropriate quality and thickness in the area. In particular, the Upper Eocene calcareous marl (Buda Marl Formation), the Lower Oligocene clays, clay-bearing silts (Tard Clay Formation and Kiscell Clay Formation), as well as the Middle Miocene clays, argillaceous marls (Badenian Clay Formation) can be considered as potencial source rocks (BONCZ et al. 2004, BADICS, VETŐ 2012, JUHÁSZ, KUMMER 1997). Source rock may also be the lower part of Tard Clay, containing overwhelmingly oil generating kerogen, and the calcareous marls of Buda Marl, in which kerogens generating mainly oil and somewhat less gas, as well as only gas generating kerogens can also be found. In the eastern part of the Hungarian Palaeogene Basin the Tard Clay is in the early phase of oil generation, therefore no substantial

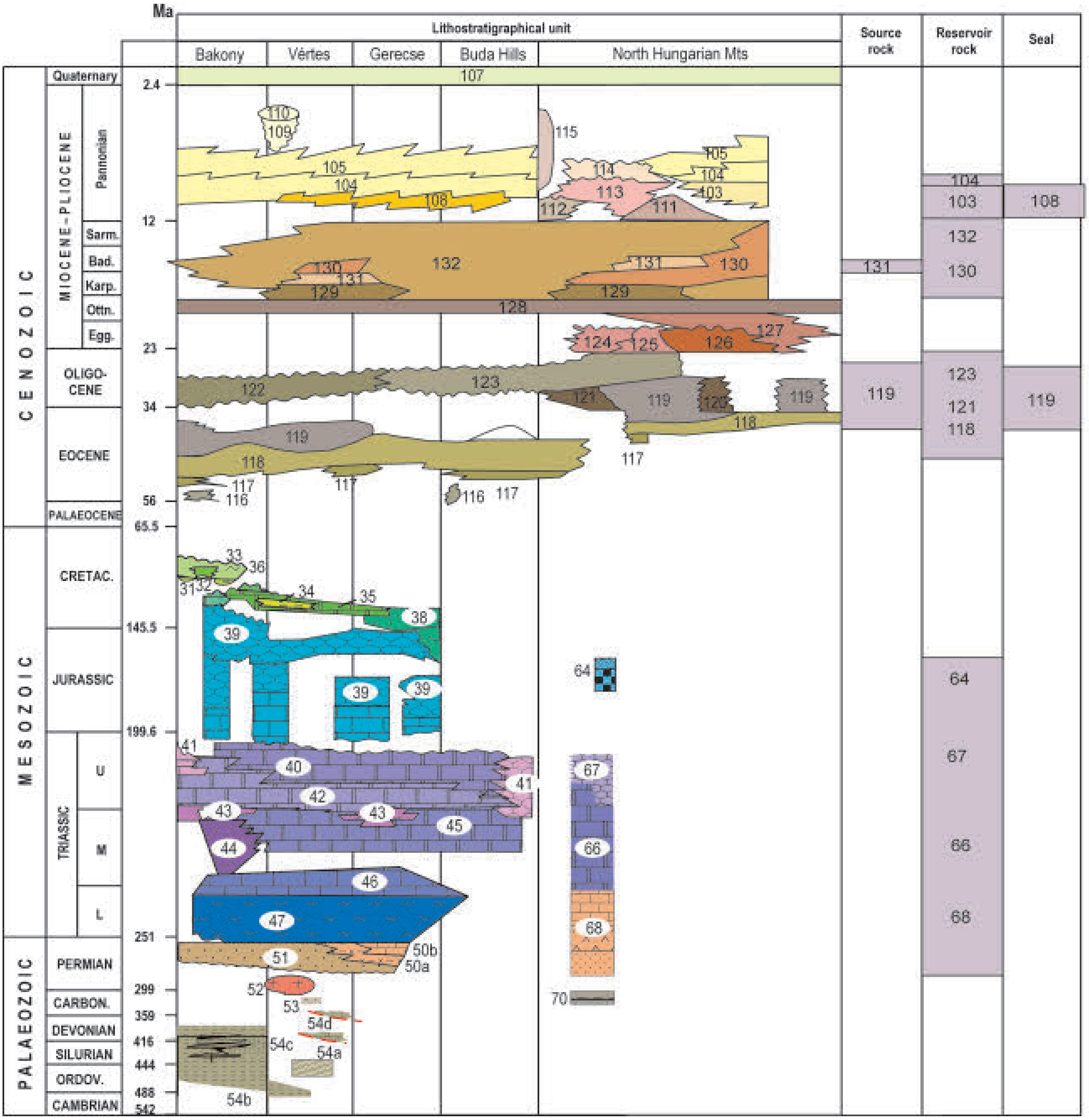


Figure 4.9.7. Theoretical stratigraphic column of the Hungarian Palaeogene Basin and the elements of the hydrocarbon systems

31. Senonian continental siliciclastic formations, 32. Senonian platform limestones, 33. Senonian basinal limestones and marls, 34. Albian continental, lacustrine and lagoonal formations, 35. Albian platform limestones, 36. Albian–Cenoman basinal marls, 37. Aptian–Albian shallow-marine limestones, 38. Lower Cretaceous flyschoid formations, 39. Jurassic – Lower Cretaceous pelagic limestones, cherty limestones, radiolarites, 40. Upper Triassic – Lower Jurassic platform limestones, 41. Norian–Rhaetian and lowermost Jurassic basinal cherty limestones, dolomites, 42. Carnian–Norian platform dolomites, 43. Carnian basinal marls and limestones, 44. Anisian–Ladinian basinal limestones, cherty limestones with tuffaceous intercalations, 45. Ladinian–Carnian platform dolomite, 46. Anisian shallow-marine limestones and dolomites, 47. Lower Triassic shallow-marine siliciclastic and carbonate formations, 50. Upper Permian shallow-marine carbonates and evaporites, 51. Middle and Upper Permian continental siliciclastic formation, 52. Upper Carboniferous – Lower Permian granitoid plutons, 53. Upper Carboniferous continental siliciclastic formation, 54. Variscan low-grade metamorphic Lower Palaeozoic formations, 64. Very low-grade metamorphic Middle–Upper Jurassic pelagic formations, 65. Middle–Upper Triassic metavolcanites, 66. Low-grade metamorphic Middle and Upper Triassic platform carbonates, 67. Very low-grade metamorphic Middle–Upper Triassic cherty limestones of toe-of-slope and basin facies, 68. Very low-grade metamorphic Upper Permian – Lower Triassic shallow-marine limestones, sandstones, marls, 70. Very low-grade metamorphic Upper Palaeozoic marine formations,

116. Eocene bauxite, bauxitic clay, 117. Eocene paralic, limnic brown coal, clay, freshwater limestone, calcareous marl, 118. Eocene shallow-marine carbonates and siliciclastic formations, 119. Eocene–Oligocene open marine formations, 120. Eocene–Oligocene andesite, pyroclastics, metasomatite, 121. Oligocene shoreline sandstone, conglomerate, 122. Oligocene terrestrial–fluvial–lacustrine clay, sand–sandstone, gravel–conglomerate, 123. Oligocene – Miocene marine – brackish water – lacustrine clay, clay marl, silt, sandstone, conglomerate, 124. Eggenburgian littoral and sublittoral, sand, loose sandstone, 125. Oligocene–Miocene schlier, 126. Egerian–Eggenburgian shallow-marine, coastal sandstone, 127. Eggenburgian fluvial-coastal plain formation, 128. Ottnangian rhyolite-rhyodacite ignimbrite deposited on terrestrial environment, 129. Karpatian Schlier, 130. Miocene volcanic formations, 131. Lower Badenian, open marine clay, clay marl, 132. Lower and Middle Miocene terrestrial, coastal and shallow-marine formations 111. Badenian–Pannonian, stratovolcanic series, 112. Badenian–Pannonian, fluvial sand, silt, rich in pyroclastics, 108. Pannonian shallow sublittoral clay marl, silt, 103. Pannonian delta slope sediments, 104. Pannonian littoral siliciclastic formation, 105. Pannonian fluvial and lacustrine siliciclastic formation, 109. Pannonian basalt, 110. Pannonian diatomite and alginite, 113. Pannonian delta plain variegated clay, silt, lignite, 114. Pannonian, coastal gravel and sand, 115. Pannonian gravel of alluvial fan, 107. Quaternary sediments

amounts of hydrocarbons could have been generated from it there. Middle Oligocene and Miocene clays and argillaceous marls are rich in organic matter (Badenian Clay Formation, Kiscell Clay Formation) — although holding sections with appropriate hydrocarbon potential — are in general immature and their hydrocarbon generation is subordinated. The C_{org} contents in the dark grey, laminated Tard Clay are 0.2–4.2 wt%, in general 1.3%, in the Kiscell Clay 0.24–0.40%, occasionally 0.5% (MILOTA et al. 1995, BONCZ et al. 2004). The younger and thermally immature Pannonian delta plains and alluvial sediments might have provided biogenic gas from their organic matter content. The potential source rocks still generate hydrocarbons up to date.

Exploration wells drilled in the HPB and the identified hydrocarbon occurrences confirmed the favourable hydrocarbon generation, migration and accumulation conditions. Based on thermal and maturation history simulations (Figure 4.9.8) the hydrocarbon generating formations were buried to the depth of oil generation conditions substantially later, in the Pannonian, 5–6 million years ago, after forming the trap structures. Thermal natural gas generation could have started from

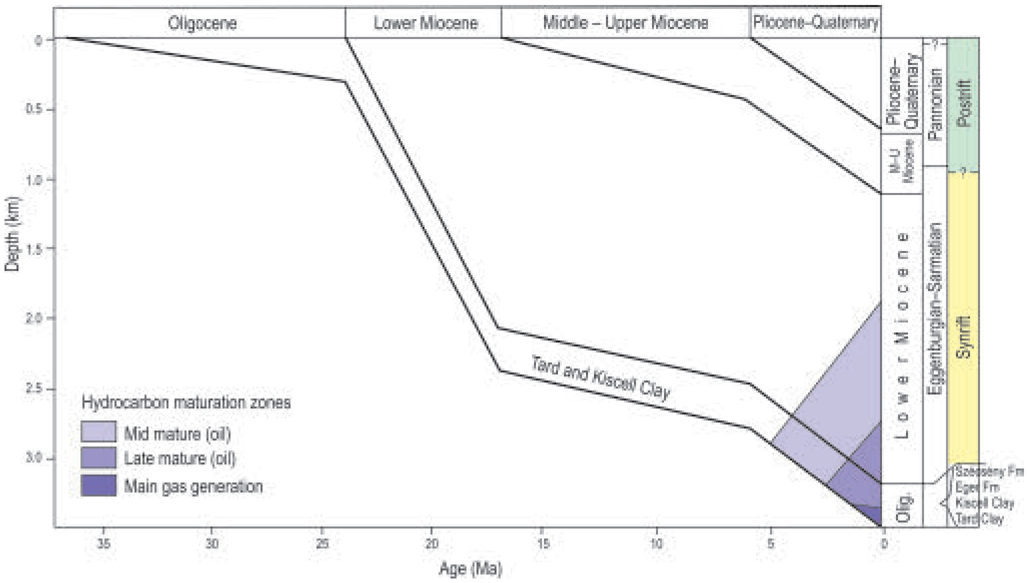


Figure 4.9.8. Burial history model of the Hungarian Palaeogene Basin (based on DOLTON 2006 and MILOTA et al. 1995)

one and half to one million years ago. The current matured source rocks are situated below 2,300–2,600 m under the surface, in the initial and main phase of oil generation, and only those in the deepest structural position could reach the phase of the wet gas generation zone in a depth of 3,400–3,800 m (KÓSA et al. 2003, BONCZ et al. 2012a).

Based on the analyses carried out, the oil in the Tóalmás-D–1 well could have been generated by a source rock with a maturity corresponding to a 0.75–0.85% vitrinite reflectance level (KISS et al. 1999). These source rocks got into the oil window approximately 5 million years ago, in the Late Pannonian, the upper boundary of which locates currently in a depth of 2,200–2,400 m in the western part of the area.

The Tard Clay, sunken into a greater depth might be the hydrocarbon source rock in the vicinity of the Darnó Zone and around the Diósjenő tectonic line. In the Salgótarján area the source rock is the calcareous-clay-bearing upper section of the Buda Marl and the clay-bearing part of the Kiscell Clay. The Nagykökényes Nk–I exploration well drilled here perforated the Tard Clay Formation in a great depth (2,000–2,400 m subsurface) and thickness. The current level of oil generation is at a depth of 2,300–2,600 m subsurface, wet gas is generated at 3,400–3,800 m, which might mean potential hydrocarbon accumulations along the Darnó wrench fault zone (KÓSA et al. 2003).

The source rock of the hydrocarbons discovered in the Gödöllő area (BONCZ et al. 2004) belongs to the Upper Eocene – Lower Oligocene Buda Marl and Tard Clay Formation. The boundary of the oil generation is at 2,200–2,400 m subsurface.

In the Transdanubian part of the basin, in the Ercsi area (BONCZ et al. 2013a) the initial and main phase of oil generation is currently located below 2,300–2,600 m, and the wet gas generation zone is below 3,400–3,800 m. Based on the vitrinite reflectance measurements 50–280 m thick Cenozoic sedimentary succession could have been denudated (SŐREG et al. 2002a). The main source rocks here are the Eocene–Oligocene sediments (Buda Marl Formation, Tard Clay Formation, Kiscell Clay Formation). The formations younger than the Oligocene are immature in the great part of the area, except the Miocene argillaceous marls, marls in the Adony–Ráckeve depression, which are found under the conditions suitable for oil generation.

In the Jászberény area (BONCZ et al. 2012a) currently the matured source rocks (Lower Oligocene clays and Upper Eocene marls) can be found in the initial and main phase of oil generation. Those in the deepest structural position (deeper

than 3,500 metres) already reached the wet gas generation zone. However, measurement data assert that no sufficient quantity of potential source rocks is present in the explored sedimentary environment.

In the North-eastern Hungarian Bátonyterenye exploration area (Boncz et al. 2012b) the Bér–1 well was drilled to discover potential Mesozoic reservoir structures. Formation gas was indicated in the 52–1,154 m depth range in Kiscell Clay Formation, and in the Tard Clay Formation (1,154–1,212 m) several times. The Tard Clay is a good source rock containing oil generating organic matter, but is merely in the early-katagenetic gas generation phase, at a low maturity level. It might have got into the oil window in the deeper part of the Zagyva Trough, but to the west from the structure explored, however, due to the unfavourable migration conditions no hydrocarbon was accumulated in the Mesozoic reservoirs. The biogenic gas generation is significant, like in the case of the Mogyoród and the Őrszentmiklós fields, to NE of Budapest.

The hydrocarbon generating rocks in the Monor area to east of Budapest (Boncz et al. 2013b) are the Upper Eocene calcareous marl (Buda Marl Formation) and the Lower Oligocene clay-bearing silt and clay (Tard Clay Formation). Currently the matured source rocks can be found in the initial and main phase of oil generation, below 2,300–2,600 metres below subsurface, and they reached the wet gas generation phase (3,400–3,800 m bss) only in the deepest structural position. The potential source rocks generate hydrocarbons up to date. The Middle Oligocene and Middle Miocene clays and argillaceous marls rich in organic matter (Badenian Clay Formation, Kiscell Clay Formation) are in general immatured, with a subordinated role (Boncz et al. 2004, 2013b).

In the Martonvásár exploration area to SE of Budapest (Boncz et al. 2001) the Baracska–1 exploration well confirmed mature source rocks younger than the Upper Cretaceous. The most probable location of the potential source rocks according to the depth conditions is the southern foreground of the Buda Mountains (Gyúró depression).

Migration

The hydrocarbon generating source rocks typical for the HPB have a very low permeability due to their pelitic characteristics. Secondary migration routes include the stratigraphic unconformity surfaces and the tectonic surface elements, hydrocarbons made their way up to the reservoir rocks along these. Migration along faults, contacts between the source rocks and reservoir rocks, the tectonic and the unconformity surface between the Mesozoic and Palaeogene rocks are very important. The presence of carrier beds deposited between source rock horizons with appropriate porosity and permeability has a beneficial impact on primary migration, which — taking into account the relatively late maturation process — is also seen as an important condition for charging the structures with hydrocarbons (Boncz et al. 2013b).

According to the maturation and burial history model of the HPB short distance horizontal and vertical migrations need to be taken into account, hence the hydrocarbons may originated from the deep zones in the vicinity of the trap. Those objects are perspective that are directly related to, or close to, source rocks (Boncz et al. 2013b). Such a short-term migration is also likely to be due to the young hydrocarbon generation and the hydrostatic pressure typical of the area. Based on the maturity of the fluid, the vertical component of migration can be reached some hundred metres away, the 500 metres can not be exceeded (Boncz et al. 2004, Hajdú et al. 1997). Migration of hydrocarbons took place along the permeable intercalations of the source rock, the formation boundaries, tectonic and unconformity surfaces.

According to the maturation and burial history models, migration at Tóalmás could have been within a short distance only, with a vertical component of a some 100 metres, but at any rate less than 500 metres. Short migration distance is due to the generation of young hydrocarbons, late migration, and the hydrostatic pressure in the formations. In the deep Jászság Basin, south of the Tóalmás area, however a long lateral migration can be assumed, during which natural gas generated there left the deeper zone of the basin. At Dány the migration distance could be up to 5–8 km.

Migration of hydrocarbons of the Monor area took and still takes place along tectonic and unconformity surfaces, and in the permeable intercalations of the matured source rock. Fault planes, contacts between the source and reservoir rocks, tectonic and unconformity surface between the Mesozoic and Palaeogene rocks are very important in the migration process. The presence of coarse grained sediment layers between source rock horizons holding appropriate porosity and permeability has a beneficial impact on primary migration (Boncz et al. 2013b). Based on the fluid maturity the vertical component of the migration can be put to a couple of hundred metres and most probably never exceeded 500 metres (Boncz et al. 2004, Szalainé et al. 1997).

In the Gödöllő area (Boncz et al. 2004) migration takes place along structural lines and permeable layers, up to only a couple of hundred metres from the place of generation. In Tóalmás the vertical component of the migration could have been a couple of 100 metres only, but in all cases less than 500 metres (Kiss et al. 1999).

In the Darnó Zone and around the Diósjenő Line the hydrocarbon migration route can be found in along the Darnó Zone structures, therefore the presence of larger amount of hydrocarbons can be assumed in the deeper zones, provided there was enough time for generation in the first place.

In the Ercsi area (Boncz et al. 2013a) short range horizontal and vertical migration must be reckoned with.

According to the studies the migration distance at Salgótarján is only a couple of hundred metres, and takes place mainly along tectonic structures. (Kósa et al. 2003).

Reservoir rocks

The reservoir rocks of the HPB are very diverse: Triassic karstified, fractured limestones (Nagykáta, Dány); Jurassic fractured, brecciated siliceous shales, limestones, silicious cemented breccia and conglomerate (Tóalmás-D); Eocene fractured, karstified limestone (Dány, Tóalmás-D); Eocene conglomerate, sandstone, breccia (Nagykáta, Gomba); Oligocene fractured argillaceous marl (Tóalmás-D); Oligocene sandstone (Mezőkeresztes); Miocene sandstones (Sülysáp-É); calcareous, tuffitic sandstones (Tura); Miocene andesite tuff, rhyolite tuff (Farmos); Lower Pannonian sandstones (Egyek); Upper Pannonian sandstones (Farmos). The porosity in the reservoir rocks varies widely, between 4 and 27%, the lowest being in the Eocene sedimentary rocks, the largest in the Upper Pannonian sandstones.

In the Darnó Zone and around the Diósjenő Line the natural gas is accumulated in sandy turbidite bodies overlying the Kiscell Clay.

In the Jászberény area (Boncz et al. 2012a) the Triassic–Jurassic carbonate formations, the Upper Eocene conglomerates, sandstones, as well as the Oligocene sandstones might be reckoned with as reservoir rocks, but potentially the Pannonian sandstones may also act as reservoir rocks in the south-eastern part of the area.

In the Salgótarján area the reservoir rocks are Oligocene and Lower Miocene sandstone layers. The following hydrocarbon occurrences and indications are known in this exploration area (Kósa et al. 2003): Nagybátony–I: gas and oil traces in Oligocene formations; Hasznos–I: oil traced Karpatian age formations; Őrszentmiklós: nearsurface biogene gas accumulation; Szirák–2 well: oil shows in the upper part of the Badenian volcanics; Szécsény–6 well: Eocene calcareous marl cemented conglomerate with inert gas reservoir; Szécsény–7 well: Upper Oligocene sandstone reservoir with combustible gas; Sóshartyán–2–3 wells: Lower-Oligocene sandstone with inert gas reservoir.

Seal rocks

Seal rocks of the reservoirs, in accordance with their respective stratigraphic positions, are created by clays and argillaceous marls of different ages. Closures of the Mesozoic reservoirs besides structural elements is ensured by the Eocene and Oligocene pelites, that is higher positioned developments of the source rocks, and their impermeable heteropic facies. The closure of the Cenozoic (Eocene, Oligocene, Miocene) traps is provided by the Lower Pannonian clays, argillaceous marls deposited above the reservoirs. The impermeable layers of the Miocene volcanic tuffs and tuffites may be reckoned with also locally (Boncz et al. 2004, Hajdú et al. 1997, Boncz et al. 2013a).

Trapping

Hydrocarbons were mostly trapped in the top zone of the elevated basin basement structures and in the pseudoanticlines formed and situated above them. Beside the structural and stratigraphic traps the combinations thereof may also occur.

Beside the traps which can be associated with the Mesozoic basement highs (reservoirs created by palaeo-geomorphological domes, Eocene–Oligocene reservoirs in the basement and in the directly overlying rocks, single reservoirs of domed structures closed by structural elements) substantial quantity of hydrocarbon was also accumulated in combined structural/lithologic traps developed within the Oligocene, Miocene and Pannonian formations (Boncz et al. 2004).

Trap types are very diverse. Hydrocarbons might have been entrapped in the western part of the HPB in the structural traps of positive flower structures created along the main strike-slip zones, or in purely compression generated reverse fault zones, eventually in the karstifited, fractured layers of carbonate formations, or reef bodies, as well as in metamorphic schists, Palaeogene volcanics, or volcano-sedimentary layers.

In the faulted Demjén area oil reservoirs can be found partly in structural, partly in lithologic traps. Reservoirs here are in shallow depth (Kőrössy 2004).

Reservoirs of the Ócsa and Monor-É area is situated in traps associated with the Mesozoic basement highs. The Mesozoic beds have been karstified in the Late Cretaceous – Early Eocene due to their terrestrial exposure, karstification can be detected in the current reservoirs. In other areas of the HPB the Mesozoic and Eocene reservoir rocks create the respective traps sometimes jointly, sometimes separately. In the Pannonian sandstones lithologic traps may also have been formed (Boncz et al. 2013b).

The occurrence of domed Miocene reservoirs can be anticipated in the Adony–Ráckeve depression (Boncz et al. 2013a).

The hydrocarbon occurrences of the Hungarian Palaeogene Basin

Data characterising the discovered reservoirs (hydrocarbon compositions, calorific values, etc.) were mostly derived from the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ), in other cases sources are indicated (Figure 4.9.9).

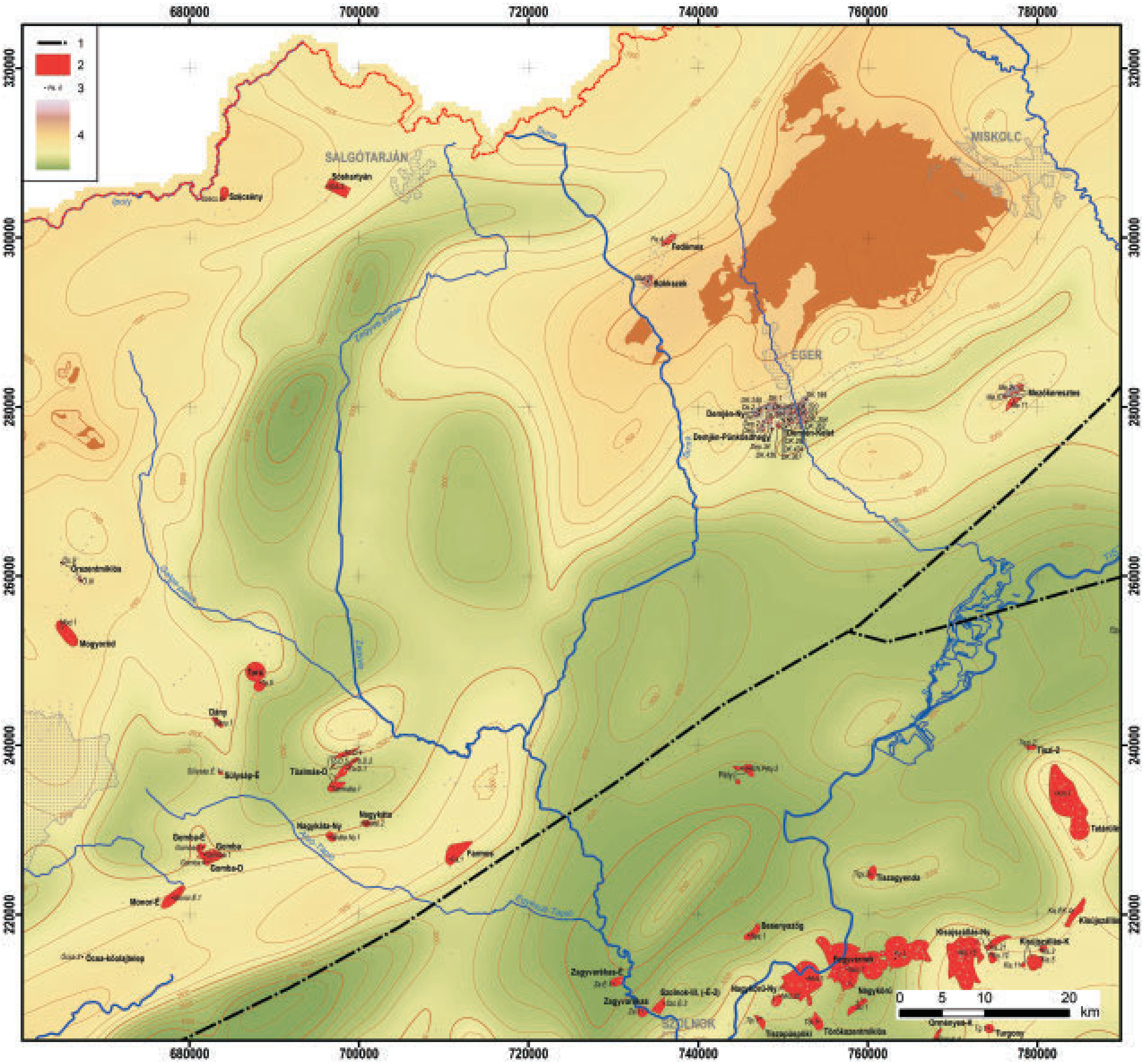


Figure 4.9.9. Hydrocarbon fields on the pre-Cenozoic basement depth map known in the Palaeogene Basin
Legend: 1. boundary of the sub-basins; 2. conventional hydrocarbon field, 3. discovery well; 4. depth of the pre-Cenozoic basement

Crude oil and natural gas occurrences in the Hungarian Palaeogene Basin

Bükkszék. The Bükkszék–1 well was drilled in 1937 on the anticline demonstrated by geological mapping (Schréter 1936, 1942), which produced 200 litres of oil daily. A total of 56 wells were drilled in the area, systematic production started on 28th of April 1937. This was the second productive hydrocarbon field in the territory of contemporary Hungary after the Budafa (Zala Basin) field. The reservoir rock of the oil includes the turbidite sandstone layers and volcanic tuff banks of the Lower Oligocene Kiscell Clay Formation. The amount of the oil exploited from the Bükkszék field up to 1st of May 1940 reached 10,000 tons (Telegdi Roth 1951).

Fedémes. The discovery well of the field with two natural gas reservoirs is the Fe–4 well, drilled in 1963. The reservoir rock is Upper Oligocene clay-bearing sandstone (Kiscell Clay Formation). Reservoirs are sealed by lithological changes. The gas-water contact (GWC) is at 105 and 128 m bsl. The combustible part of the natural gas accumulated is 81.4% in the upper reservoir, 65.1% in the lower one. The calorific value is 30.6 and 29.2 MJ/m^3, its methane content (CH_4) is 79.1 and 57.6%, respectively, the carbon dioxide contents (CO_2) are 0.8 and 3.9%, the nitrogen gas (N_2) 18.7 and 31.2%, but no data are available for the C_{5+} contents (the part containing hydrocarbon compounds with more than 5 carbon atoms).

Demjén. The oil field is divided up into three parts. The area called today *Demjén West* was the scene of the first oil discovery at the De–1 well in 1954. Oils were identified in the *Demjén East* in 1956 by the DK–1 well, in *Demjén Pünkösd-*

hegy in 1962 by Dep–2 well. The reservoirs are situated in the strongly fragmented blocks displaced relative to each other, in the turbiditic, clay-bearing sandstone layers of the Lower Oligocene Kiscell Clay. The technologically recoverable volume of the raw material from a single well was small.

The oil-water contact (OWC) in the Demjén West field is at 221 m bsl. The density of the paraffinic oil is is 830 kg/m^3, sulphur content 0.3%, the dissolved gas content is minimal. The OWC in the Demjén East field can be defined in a depth of 1,200 m bsl. The density of the intermediate oil is 833 kg/m^3, sulphur content 0.3%, dissolved gas content 90 m^3/m^3. The combustible part of the dissolved gas is 98.0%, the calorific value is 46.9 MJ/m^3. The methane content of the gas is 81.4%, CO_2 0.3%, N_2 1.8%. In Demjén Pünkösdhegy paraffinic type oil is known, its density is 868 kg/m^3, sulphur content 0.3%, dissolved gas content 40 m^3/m^3. The combustible part of the dissolved gas is 98.0%, the calorific value is 48.1 MJ/m^3, CH_4 81.4%, CO_2 0.3%, N_2 1.8%.

Mezőkeresztes. The discovery wells were Me–2 drilled in in 1951, Me–11 in in 1952 and Me–63 in 1953. The exploration well marked Me–1, deepened to a depth of 1,400 metres to the Oligocene strata was the first in the Mezőkeresztes field, but due to technical problems the test process of the well could not be completed, therefore the Me–2 has become the first successful well finding several oil and gas shows and it was put into production. Hydrocarbon production was in progress from the Mezőkeresztes field in the period between 1951 and 1976. A total of seven reservoirs are known in this field.

The lowermost, undersaturated *oil reservoir with carbon dioxide* (CO_2) gas contents is known in combined structural–lithologic trap in Eocene limestone overlying Triassic dolomite, with an OWC depth of 1,365 m bsl. The oil density is 884 kg/m^3, the combustible part of the dissolved gas is 25%, the calorific value is 5.3 MJ/m^3. CO_2 contents 48%, N_2 contents 27%.

The reservoir rock of the *Me–5K oil reservoir* with gas cap is the Oligocene clay-bearing sandstone (Kiscell Clay Formation), the OWC depth is 1,340 m bsl. The density of the paraffinic oil is 857 kg/m^3, the combustible part of the cap gas is 30%, the calorific value is 10.1 MJ/m^3. The *Me–5Ny oil reservoir*, named “Lattorfian” and “Rupelian” have an OWC depth at 970 and 1,220 m bsl, respectively. The reservoir rock is Oligocene sandstone. The density is 858 kg/m^3, the combustible part of the dissolved gas is 34–63%, the calorific value is 5.3–27.2 MJ/m^3.

The *Rupelian I and II free gas reservoirs* have a GWC depth around 1,340 m bsl. The reservoir rock is also Oligocene sandstone. The combustible part of the gas is 6%, the calorific value is 2.9 MJ/m^3.

Dány. The discovery well of the field with a single undersaturated *oil reservoir* is the Dány–1 drilled in 1994. The OWC depth lies at 1,550 m bsl. The *Eo–T* reservoir consists of two reservoir horizons: the upper section of the reservoir rock is built up of Eocene limestone and calcareous marl, the lower one is fractured, slightly dolomitised Triassic limestone. In the latter there are a lot of karstic cavities, the drilling bit dropped as much as 2–6 metres during drilling (SZALAI et al. 1997). The density of the paraffinic oil density is 871 kg/m^3, the dissolved gas content is 20 m^3/m^3. The combustible part of the dissolved gas is 6.5%, the calorific value is 2.9 MJ/m^3, CH_4 5.8%, CO_2 78.8%, N_2 14.7%, the C_{5+} content is 6 g/m^3.

Gomba. The Gomba field includes the *Gomba Central* reservoir discovered by the Gomba–1 well in 2003, *Gomba North* explored by the Gomba–5 well in 2006, and *Gomba South* was identified by the Gomba–4 well also in 2006.

The *Gomba Central oil reservoir* settled on a structural dome, is the highermost member of the Mesozoic Gomba structure group. The depth of the OWC was determined as 2,235 m bsl. The reservoir rock of the undersaturated oil reservoir is the Triassic fractured limestone temporarily classified in the Kisfennsík Limestone Formation and the overlying Eocene clastic succession (Kosd Formation?) sandstone, gravelly sandstone and conglomerate formations. The accumulated oil is paraffinic, its density is 852 kg/m^3, the dissolved gas content is 40 m^3/m^3. The combustible part of the gas is 41.5%, the calorific value is 18.3 MJ/m^3. Its methane content is 36.9%, CO_2 52.8%, N_2 5.7%, the C_{5+} content is 37.1 g/m^3. The lower boundary of the *Gomba North oil reservoir* can be defined at a depth of 2,300 m bsl. The reservoir rock is Eocene sandstone, gravelly sandstone, conglomerate. Intermediate oil is accumulated here, with an average density of 859 kg/m^3. The combustible part of the dissolved gas is 92.8%, the calorific value is 48.8 MJ/m^3. The lower boundary of the *Gomba South oil reservoir* is at 2,282 m bsl The reservoir rock is also Eocene sandstone, gravelly sandstone, conglomerate. Based on the figures of the well-log interpretation the Eocene reservoir rock has primarily matrix porosity, but the storage capacity is increased also by the fractures caused by tectonic impacts. The density of the paraffinic oil is 869 kg/m^3. The dissolved gas content is 31 m^3/m^3, the combustible part of the dissolved gas is 51.1%, the calorific value is 20.0 MJ/m^3.

Monor North (Monor-Észak). The Monor North *“Eocene”* undersaturated *oil reservoir* was discovered by the Monor-É–1 exploration well drilled in 1997 in Eocene sandstone–conglomerate reservoir rocks. The OWC depth is at 2,907.5 m bsl. The oil was accumulated in a domed structural trap subjected to a heavy tectonic impact. The density of the intermediate oil is 870 kg/m^3, the dissolved gas content is 5 m^3/m^3. The combustible part of the gas is 58.0%, the calorific value 31.1 MJ/m^3, CH_4 44.6%, CO_2 36.4%, N_2 5.6%, the C_{5+} content is 110 g/m^3. Typical geophysical well logs from Monor-North–1 well are seen on Figure 4.9.10.

Nagykáta. The undersaturated oil occurrence was discovered by the Nkáta–2 well in 2001. The depth of the OWC is at 2,051.5 m bsl. It is a multiple reservoir, the reservoir rock is the Upper Triassic, fractured, karstified limestone, dolomitic limestone (similarly to the Kisfennsík Limestone in the Bükk Mountains) and the overlying Eocene breccia–conglomerate

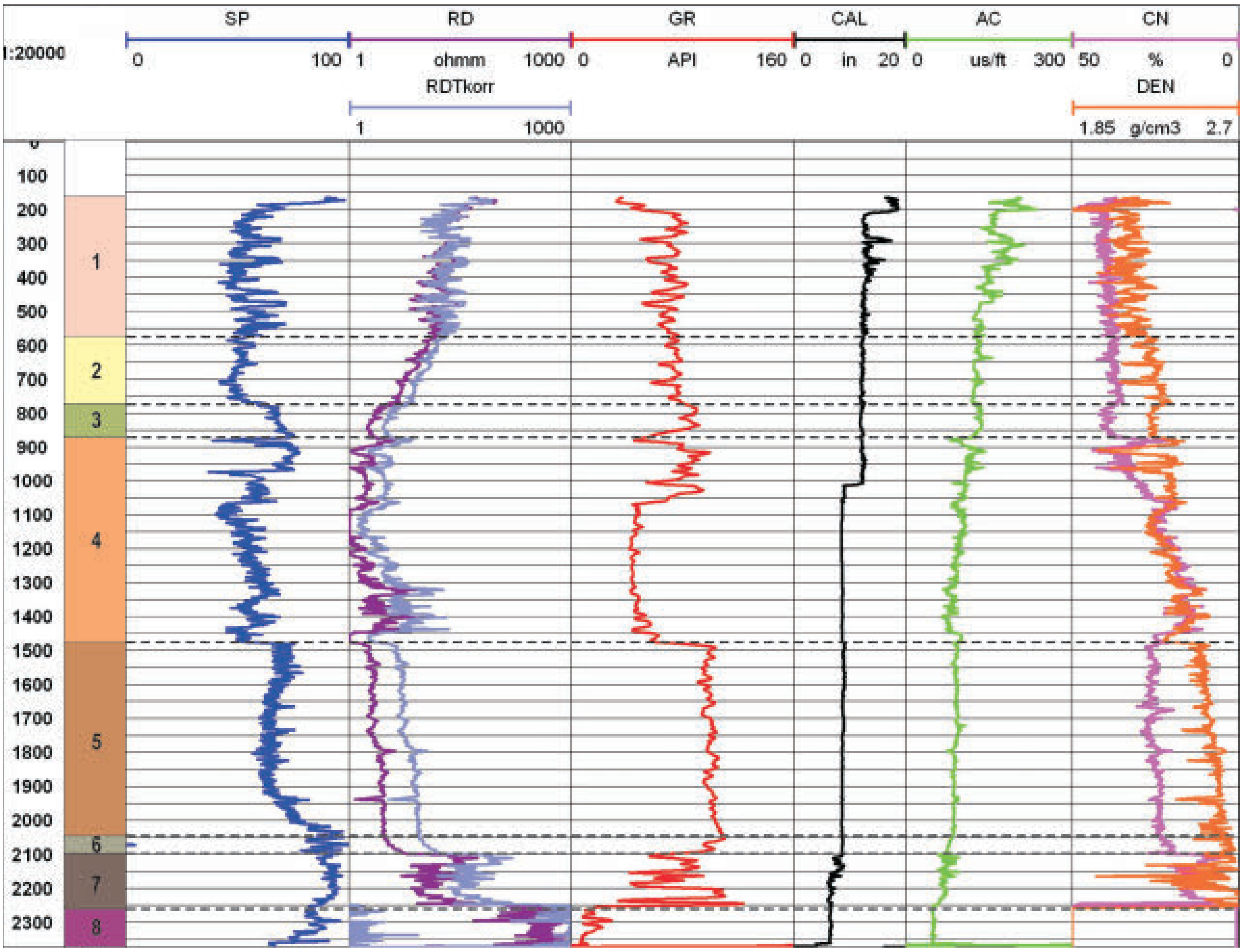


Figure 4.9.10. Typical geophysical well logs of the Monor-Észak-1 well

Legend: SP: spontaneous potential, R,RDT: electrical resistivity; GR: natural gamma-ray; CAL: caliper log; AC: acoustic profile; CN: compensated neutron, DEN: density profile. *Geological column:* 1. Újfalu Fm, 2. Algyő Fm, 3. Endrőd Fm, 4. volcanic and sedimentary Upper Oligocene –Lower Miocene formations, 5. Kiscell Clay Fm (Oligocene), 6. Tard Clay Fm (Oligocene), 7. Buda Marl Fm (Upper Eocene – Oligocene), 8. Upper Triassic limestone

with the karstified limestone (similar to the Szépvölgy Limestone) which constitute a single hydrodynamic system. The density of the paraffinic oil is 835 kg/m^3, the dissolved gas content 80 m^3/m^3, the calorific value of the dissolved gas 24.7 MJ/m^3, the combustible part 50.0%, CH_4 40.0%, CO_2 content 45.5%, N_2 4.5%, the C_{5+} content is 87 g/m^3. The oil contains 11,784 g/m^3 condensate, which is prominent in national terms.

Nagykáta West (Nagykáta-Nyugat). The undersaturated oil reservoir was discovered by the Nagykáta-Ny–1 exploration well drilled in 2012 in the Upper Triassic fractured limestone (Kisfennsík Limestone) reservoir rock, at an OWC depth of 2,533 m bsl. The oil was accumulated in a domed structural trap. Capping of the trap is ensured by the predominantly argillaceous marl Eocene formations overlying the Triassic limestone and the Oligocene Kiscell Clay above them. The density of the paraffinic oil is 838 kg/m^3, the dissolved gas content is 59 m^3/m^3. The combustible part of the dissolved gas is 50.1%, the calorific value 19.9 MJ/m^3, CH_4 44.6%, CO_2 44.4%, N_2 5.5%, the C_{5+} content is 8 g/m^3.

Ócsa. The undersaturated oil reservoir was discovered by the Ócsa–2 exploration well drilled in 2009 in Eocene conglomerate and limestone breccia reservoir rocks, at an OWC depth of 1,614 m bsl. The oil was accumulated in a morphologically formed stratigraphic trap. The oil is paraffinic, the dissolved gas content is 13.4 m^3/m^3. The combustible part of the dissolved gas is 72.2%, the calorific value is 29.3 MJ/m^3, CH_4 67.1%, CO_2 content 22.6%, N_2 5.2%, the C_{5+} content is 42 g/m^3.

Sülysáp North (Sülysáp-Észak). The undersaturated *oil reservoir* named *M-1* was discovered by the Sülysáp-Észak–1 well drilled in 2008. The well did not find any hydrocarbon in the Triassic and Eocene formations, but an oil reservoir was identified in Miocene sandstone, glauconitic sandstone beds (Pétervására Sandstone Formation) at an OWC depth of 970.6 m bsl. The oil was accumulated in a domed structural trap effected by strong tectonic impact. The reservoir is traversed by a fracture with NNE–SSW strike near the well interpreted on seismic sections, which is a related to the strike-slip zone running to the south-east and named Tóalmás (Balaton) Line. The density of the paraffinic oil is 891 kg/m^3, dissolved gas

content 5 m^3/m^3, combustible part 86.6%, calorific value is 35.3 MJ/m^3. Its methane content is 77.7%, CO_2 0%, N_2 13.4%, the C_{5+} content is 11 g/m^3.

Tóalmás South (Tóalmás-Dél). The discovery wells of the field are the Tó-D–1 (1999), the Szentmártonkáta Szmkáta–1, the Tó-D–2 (2001), the Tó-D–4 (2002) and the Tó-D–5 (2011) wells. The reservoirs are found in fractured, brecciated Jurassic siliceous shale, silica, quartziferous limestone reservoirs and Eocene limestone (Szépvölgy Limestone Formation), or fractured Oligocene argillaceous marl (Tard Clay Formation). The porosity of the Jurassic reservoir rocks is 13–24%, that of the Palaeogene is at around 5.7%. Pressure in the reservoirs is of hydrostatic origin and stays at 24.3–24.7 MPa, the temperature is 124–135 °C. The condensate content of the gas is 182–212 g/m^3 (BONCZ et al. 2004).

There are three undersaturated oil reservoirs known in the field (Tóalmás–I, –III, –IV) and two gas condensate reservoirs (Tóalmás–II, Szentmártonkáta).

The *Tóalmás–I oil reservoir* was explored by the Tóalmás-D–1 well and the Tóalmás-D–3 well drilled in 2001. The OWC depth of the reservoir is at 2,404 m bsl. The reservoir rock of the is fissured, brecciated Jurassic quartziferous shale, limestone and quartziferous limestone. The seal is provided by the upper part of the formations and by the overlying Eocene clastic and marl beds. The density of the intermediate oil is 859 kg/m^3, the dissolved gas content is 143 m^3/m^3, the combustible part 33.7%, the calorific value 18.0 MJ/m^3, CH_4 25.4%, CO_2 60.8%, N_2 5.5%, the C_{5+} content is 69 g/m^3. The lateral boundary of the reservoir is provided by the deepening of the reservoir rock in dip direction. In the line of strike the closure is assisted by tectonic elements and the deepening in NE direction. Separation to the SW from the Szentmártonkáta gas condensate reservoir is provided by the structural deepening. It is separated from the Tóalmás–II gas condensate reservoir by a fault.

The *Tóalmás–II gas condensate reservoir* was discovered by the Tóalmás-D–2 well. The GWC depth is at 2,338.5 m bsl. The Jurassic reservoir rocks have appropriate permeability and reservoir porosity due to the fragmentation, fracturing and karstification. The upper part of the reservoir rocks is siliceous schist, consisting of crypto-crystalline silica particles and radiolaria with carbonate intercalations. The best part of reservoir lies under this, consisting of quartz and chert. The underlying beds are low porosity limestones. The pressure is hydrostatic. The combustible part of the natural gas is 25.3%, the calorific value is 11.4 MJ/m^3, CH_4 22.0%, CO_2 61.4%, N_2 13.3%, the C_{5+} content is 31 g/m^3. The condensate is of intermediate type.

The *Szentmártonkáta gas condensate reservoir* was discovered by the Szmkáta–1 well, drilled in the SW member of the Tóalmás South structural range. The extension of the reservoir is determined by the deepening of the reservoir in most directions. The western–north-western boundary is a fault. The GWC depth is at 2,352 m bsl. Good permeability and reservoir porosity are provided by the fissures and vugs of the Jurassic breccia (chert, limestone, radiolarite) and strongly fragmented limestone reservoir rocks. The reservoir pressure is hydrostatic, the gas is saturated. The combustible part is 36.6%, the calorific value is 17.2 MJ/m^3. Its methane content is 29.5%, CO_2 54.1%, N_2 9.3%, the C_{5+} content is 42 g/m^3. The condensate of the reservoir is of paraffinic type.

The *Tóalmás–III undersaturated oil reservoir* was discovered by the Tóalmás-D–4 well drilled in 2002. The reservoir structure was developed in an en-echelon type tectonic system of a strike-slip zone (Tóalmás Line). The OWC depth is at 2,182 m bsl. The sedimentary sequences of Tard Clay and Upper Eocene carbonates and marls obtain their reservoir capacity from their fractured, fragmented nature, they constitute a unified hydrodynamic system. The reservoir consists of two, clearly distinguishable parts. 1. Oligocene argillaceous marl (Tard Clay Formation): fractured clay-marl with shear foliation zones and somewhere cavities which resulted good permeability and 5–9% total porosity. 2. Eocene biogenic limestone (Szépvölgy Limestone Formation): the limestone is of low porosity, no penetrable fissures can be found in it. The oil is of intermediate type, without a petroleum fraction. Its density is 847 kg/m^3, the dissolved gas content is 119 m^3/m^3, the combustible part 92.7%, the calorific value 61.2 MJ/m^3. Its methane content is 54.0%, CO_2 6.0%, N_2 1.3%, the C_{5+} content is 324 g/m^3.

The *Tóalmás–IV undersaturated oil reservoir* was discovered by the Tóalmás-D–5 well drilled in 2011. The reservoir rocks are Eocene tuff, silt containing limestone and sandstone. The oil was accumulated in one of the domed, fault bordered structural traps of the strongly tectonised Tóalmás South structure. The OWC depth of the reservoir is at 2,206 m bsl. There is a slight overpressure in the reservoir. The density of the intermediate oil is 891 kg/m^3, the dissolved gas contents 5 m^3/m^3, the combustible part 92.0%, the calorific value is 38.3 MJ/m^3, CH_4 75.3%, CO_2 7.0%, N_2 1.0%, the C_{5+} content is 17 g/m^3.

Tura. Three oil and one free gas reservoirs are in the field which has become known by the Tu–5 well drilled in 1991. Reservoir rocks are constituted by Lower and Middle Miocene sandstone, calcareous, tuffitic sandstone, as well as wheathered tuffitic sandstone and limestone. The reservoir rock of the *undersaturated oil reservoir* marked *Tura M–1* consists of Sarmatian limestone, the OWC depth is at 717 m bsl. The density of the intermediate oil is 924 kg/m^3, the dissolved gas contents is low, no data are available on the composition. The *M–2 free gas reservoir* explored by the Tu–6 and –7 wells is situated in Karpatian and Badenian tuffitic sandstone, the GWC depth is at 717 m bsl. The combustible part of the gas here is 98.3%, the calorific value is 35.3 MJ/m^3, CH_4 98.2%, CO_2 0.05%, N_2 1.7%, the C_{5+} content is 1 g/m^3. The *M–3 oil reservoir with gas cap* was known by the Tu–7 well. The reservoir rock is Lower Miocene Karpatian sandstone. The OWC depth is at 717 m bsl. The density of the intermediate oil is 921 kg/m^3. The combustible part of the cap gas is 97.1%,

the calorific value is 35.0 MJ/m^3. Its methane content is 97.1%, CO_2 1.7%, N_2 1.2%, the C_{5+} content is 1 g/m^3. The *M–4 undersaturated oil reservoir* was drilled by the Tu–8 well, its OWC depth is at 842 m bsl, the reservoir rock is Lower Miocene Karpatian sandstone. The density of the intermediate oil is 822 kg/m^3. The combustible part of the gas is 97.7%, the calorific value 44.1 MJ/m^3, CH_4 85.6%, CO_2 1.3%, N_2 1.0%, the C_{5+} content is 62 g/m^3.

Natural gas occurrences of biogenic origin in the Hungarian Palaeogene Basin

Őrszentmiklós. The presence of natural gas was known from the water wells drilled in the 1911–14 and 1935–36 periods, but the occurrence was actually explored by the Ős–9 well in 1954. The Őrszentmiklós (Őrbottyán) natural gas occurrence can be found in a pseudoanticline structural trap in Oligocene, clay-bearing sandstone beds overlying an Upper Triassic dolomite and limestone block. The depth of the GWC is at 125 m bsl. The combustible part of the natural gas is 98.4%, the calorific value is 37.2 MJ/m^3. Its CH_4 content is 97.8%, CO_2 0.1%, N_2 1.5% (Völgyi et al. 1985). It is considered of biogenic origin based on the gas composition and of the nearsurface location. The small scale (11 Mm^3) gas reservoir discovered was used as an underground gas storage up to the 1960s (Kőrössy 2004).

Mogyoród. The field was discovered by the Mogyoród Mód–1 exploration well drilled in 1993. Four natural gas reservoirs have become known. The Mogyoród occurrence can be found next to the Őrszentmiklós gas occurrence on the ascending north-western edge of the HPB. The hydrocarbon inflows were received from the reservoirs made up of Kiscell Clay sandstone beds. Gases in the Mogyoród reservoir are of biogenic origin generated near to the surface and accumulated at a depth of 423–646 m bsl in Oligocene clay-bearing, silt containing sandstone beds. Sandstones are deposited in thin beds belonging two sandstone group and are named from the bottom to up as follows: Ol–II–1, Ol–II–2 and Ol–III–1, Ol–III–2. Gases were accumulated in pseudoanticline structural traps following the morphology of the Eocene Triassic basin basement. Reservoirs contain predominantly dry gas consisting of methane. The combustible part of the gas is 95.5–96.6%, the calorific value is 34.4–34.7 MJ/m^3. The CO_2 content is 0.02–0.3%, N_2 3.3–4.2%.

Natural gas occurrence in Lower Pannonian reservoir in the southern edge of the Hungarian Palaeogene Basin

Farmos. The occurrence containing four free gas reservoirs was discovered by the Fa–1 well in 1963, on the southern edge of the HPB. It does not belong to the Palaeogene hydrocarbon system. The reservoir rocks are Miocene volcanics and Upper Pannonian sandstones. The *Miocene gas reservoir* is situated in a stratigraphic trap under the erosional surface of the volcanic cone, the Upper Pannonian reservoirs are known in lithologic traps of the overlying dome. The GWC depth of the Miocene reservoir is at 1,215 m bsl, the reservoir rock is andesite and rhyolite tuff. The combustible part of the natural gas is 51.6%, the calorific value is 21.3 MJ/m^3, CH_4 49.8%, CO_2 47.2%, N_2 1.2%, the C_{5+} content is 16 g/m^3. The GWC depths of the *Pl2–I–II–III free gas reservoirs* known in Upper Pannonian sandstones are 1,098, 1,112 and 1,128 m bsl, respectively. The combustible part of the gases is 44–66%, the calorific value 21.0–24.1 MJ/m^3, CH_4 54.6–65.2%, CO_2 0.2–1.8%, N_2 33.6–41.9%, the C_{5+} content is 9–29 g/m^3.

High inert containing natural gas reservoirs in the northern part of the Zagyva Trough

Szécsény. High CO_2 and N_2 content gas reservoirs were discovered in Lower Oligocene conglomerate (Hárshegy Sandstone Formation) overlying the Variscan metamorphic basement, at a depth of 760 m bsl (GWC) by the Szécs–6 well and in Upper Oligocene sandstone (Kiscell Clay Formation) 37 m bsl by the Szécs–7 well in 1964 (Trócsányi et al. 1972). The combustible part of the natural gas in the lower reservoir is 7.6%, the calorific value 3.4 MJ/m^3, CH_4 6.1%, CO_2 61.9%, N_2 30.5%. The combustible part of the gas in the upper reservoir is 30.7%, the calorific value 12.1 MJ/m^3, CH_4 27.4%, CO_2 2.1%, N_2 67.2%.

Sóshartyán. Natural gas reservoir is known in the Sós–2 and –3 well drilled in 1971 in the turbidite sandstone of the Lower Oligocene Kiscell Clay. The combustible part of the gas is 4.1%, the calorific value is 2.1 MJ/m^3. Its methane content is less than 4%, the CO_2 content is 90.5%, the N_2 5.4%.

Exploration and production methods

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5

Geological and geophysical surveys — from data acquisition to interpretation

The most expensive part of the hydrocarbon exploration is the drilling, so precise positions of the wells have to be determined prior to drilling on the basis of all available geological and geophysical information. Recognition of the subsurface formations and structures is performed by geological mapping, as well as processing and interpretation of several types of the geophysical data. The Bouguer anomaly gravity map has remained one of the basic maps in hydrocarbon exploration, ever since the research of Loránd Eötvös (1848–1919), a pathfinder in Hungarian geophysics. Gravity maps are also essential for planning detailed seismic surveys due to their ability to image gravity anomalies, like anticline structures having special importance in hydrocarbon accumulations (Figure 5.1).

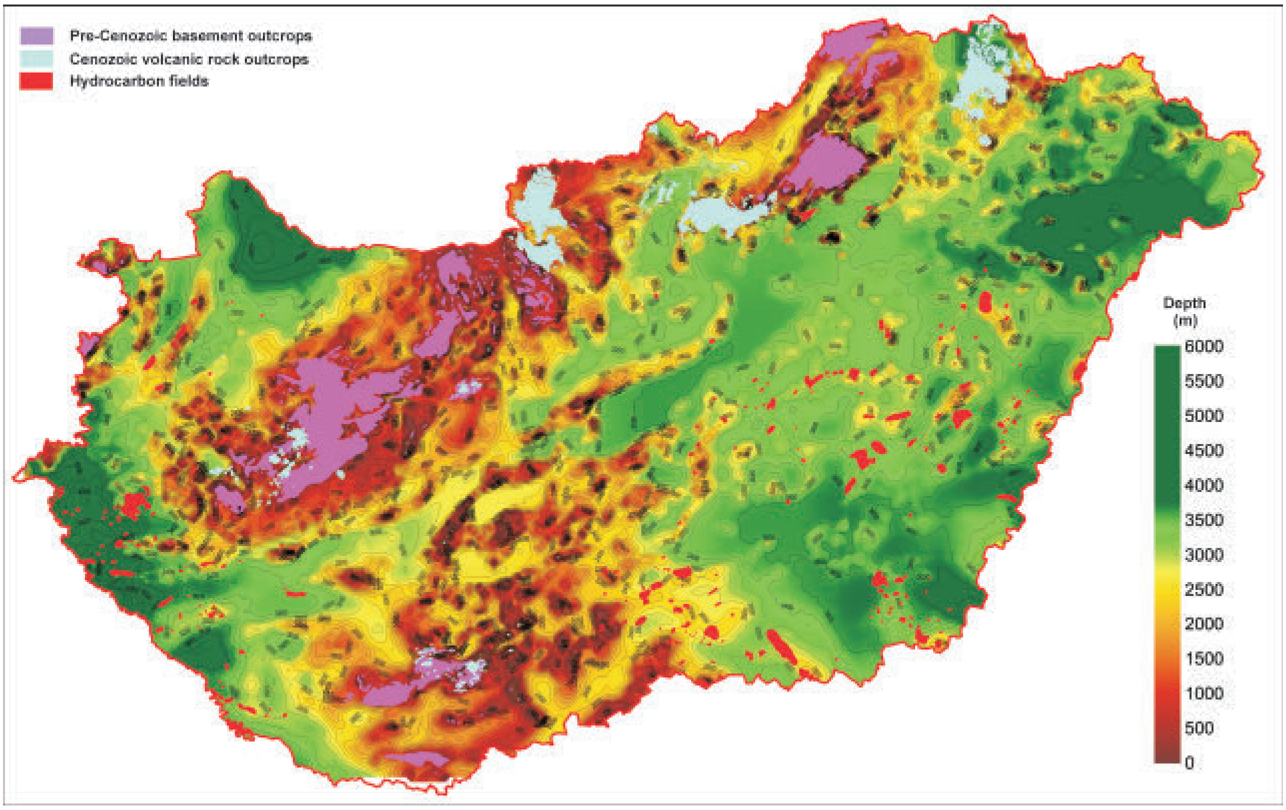

Figure 5.1. Inverted gravity depth map with basement outcrops, outcropped igneous rocks and hydrocarbon accumulations

The most important aim of gravity data processing and interpretation is the determination of different blocks with different densities, for example with edge detection, which allows assigning a complex net of the gravity lineaments in the study area. A gravity lineament is a linear object, which has geological formations with different densities on their two sides with relatively sudden density changes. In most cases, those lineaments are of tectonic origin but anomalies caused by density variations of magmatic activity or metamorphic processes cannot be excluded either. Gravity anomalies from different depths may be superimposed, however, they can be separated from each other calculating the maps for certain depths. Anomalies can also be investigated along a 2D vertical profile, by changing the density values, to estimate the model that generates the observed gravity field. To obtain the most probably model, semi-automatic and automatic (modelling and inversion) data processing

methods are applied. The more geological and geophysical information is utilised in these procedures; the more accurate density model will be calculated at the end. It is important to mention that the same gravity response can be observed above different geologic models, in other words the possibility of geological equivalences has to be considered.

If only few seismic profiles and borehole data is given in the study area, more additional information is needed for either the further survey planning or the interpretation of the available data. For this reason, utilisation of geophysical (gravity or magnetic) mapping is highly recommended to connect seismic and borehole datasets located far away from each other. Spatial interpolation and extrapolation of sparsely located 2D seismic and borehole data are highly supported by the geophysical potential field maps. It has to be noted that the gravity method works based on the density of the geological formations and seismic is based on the variations of acoustic impedance, which is the product of the density and wave propagation velocity. The integrated interpretation of the gravity, seismic, and borehole geology data has possibilities that are unexploited in many cases. We can follow reflection horizons (i.e. lithological boundaries) along the seismic sections, and after depth conversion, we can compare them to the Bouguer anomaly data obtained from territorial gravity surveys. In sedimentary basins, the highest energy reflections are usually observed from the top of the pre-Cenozoic basement, so they can be tracked with the help of the borehole data located close to the seismic profile. Comparing the depth variations of the top of basement derived from seismic interpretation with the variations of the basic (or filtered) gravity Bouguer anomaly maps, we are able to establish mathematical relationships between those. In this way, it is possible to get correlations between the seismic and gravity depth data. Based on these correlations, it is also possible to track the top of the pre-Cenozoic basement in the areas of a sedimentary basin where seismic sections are not available, or they do not have high energy signals for any reason.

Hydrocarbon exploration professionals mostly predict potential hydrocarbon reservoirs on the basis of seismic data. 2D seismic sections image geological formation and structures right beneath the seismic profiles, while 3D seismic surveys visualise the subsurface beneath the survey areas on vertical and horizontal slices for the purpose of precise determination of the locations of exploration wells.

Reflection field surveys are carried out by the observation of elastic waves generated on the surface and reflected from the lithological boundaries. The source of the waves can be an explosive charge loaded in small-diameter shallow holes, or a seismic vibrator installed on a vehicle to shock the ground by high energy vibrations. Implementation of seismic surveys sometimes requires a huge effort on the surface: personnel of dozens of field workers, several vehicles, vibrating machines or explosive sources, recording instruments and additional equipment are also needed. On those scores, seismic surveys may impair the environment therefore special permissions are required from the authorities prior to the data acquisition. Beside the surface seismic exploration, results of ground or airborne gravity, geomagnetic, electrical, and magneto-telluric surveys are also integrated into the investigated geological model. Unfortunately these methods, although they burden the survey area only in a negligible or not in any rate, their resolution is usually not adequate for establish a detailed, high resolution reservoir model.

Seismic methods utilised in the hydrocarbon exploration, mostly the reflection data processing and interpretation techniques, went through a great progress in the past few decades. Adaptation of the new methods and techniques in the investigation of hydrocarbons in the Pannonian Basin was also successful. Seismic reflection sections provide us an opportunity to trace lithological boundaries, geological sequences, faults, fault zones, and structural or stratigraphic traps. Based on the seismic sections, it is possible to assign prospective geological traps for hydrocarbon accumulation; however, the question is always whether these traps really have fluids? Here we summarise those data processing and interpretation procedures that can help us to answer this most important question.

Seismic attribute sections highlight several properties of the observed data that can help to understand the lithological and structural features along a seismic profile. One of the key information is the *reflection strength* which represents the reflectivity of the lithological boundaries, as well as the inner structure of the geological formations. This attribute maps very well the lithological changes, fault zones, and the blocks located between the faults or fault zones. Another, useful seismic attribute is the *instantaneous phase* that indicates the reflections independently from their amplitudes (energy) supporting the tracking of weak reflections, as well as the recognition of the reflection configuration in the seismic sequences and geological blocks. These, so-called, Hilbert-attributes (TANER et al. 1979) can easily be calculated for predicting potential hydrocarbon traps. Other reflection attributes are also successfully utilised in petroleum exploration, calculated usually from 3D datasets, such as *coherency* and *curvature* parameters (MARFURT et al. 1998, CHOPRA, MARFURT 2007). It has to be noted that the above mentioned seismic attributes can be easily calculated and they provide very useful information; however, none of them can confirm the presence of any fluids in the trap.

Direct hydrocarbon indicators (HILTERMAN 2001, BROWN 2004) were introduced into the reflection exploration to predict the probability of the fluid content of the prospective structures and to reduce the risk of dry wells. Such kind of features are, for example the *flat spots*, which are near horizontal reflections observed in the stratigraphic structures possibly indicating a fluid boundary within the reservoir (for instance oil and gas). At the terminations of those flat reflections, polarity changes can be also detected due to the change of the sign of reflection coefficient. Depending on the acoustic impedance variations related with the lithology of the reservoir, the indicative reflections can be recognised on the seismic data as high energy anomalies (*bright spots*) or as low energy (*dim spots*) anomalies. They are characterised by their seismic

amplitudes compared to the background amplitude values.

Dim spots usually appear in overpressured reservoirs, when the high pressure weakens also the inner structure of the covering rocks and lowers their acoustic impedance. The bright spots are easily recognisable on the conventional seismic sections or on their reflection strength attribute. To detect a dim spot studying the instantaneous phase attribute is the best choice.

In Figure 5.2, a seismic bright spot detected just beneath the top of the Mesozoic basement is displayed on the enlarged part of PGT–4 section (Posgay et al. 1996). Reflection data was collected, processed, and interpreted by the Eötvös Loránd Geophysical Institute of Hungary (MÁELGI). After detailed analyses of the seismic amplitude anomaly, the Medgyesbodzás–4 exploration well hit a small hydrocarbon reservoir in the carbonate rocks.

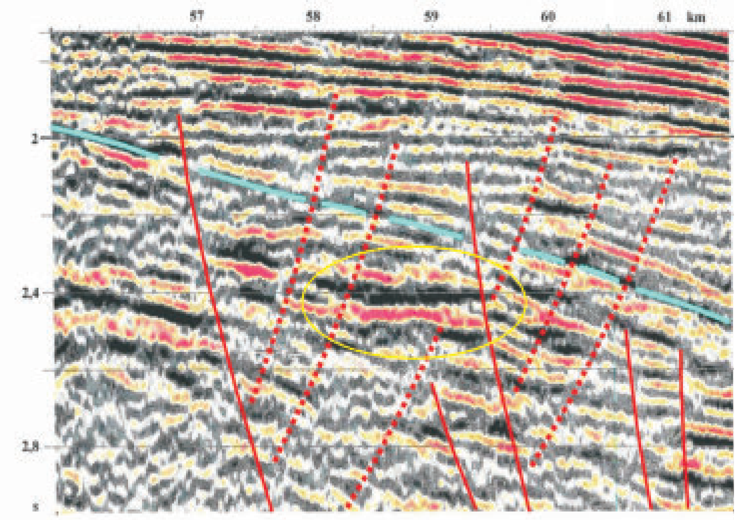

Figure 5.2. Bright spot detected within the Mesozoic basement at the western flank of Békés Basin

This enlarged part of PGT-4 reflection section is colored by the seismic amplitude. The interpreted blue surface is the top of the Mesozoic basement, and red lines mark the presumable faults (modified after Posgay et al. 1996)

A few decades ago, it happened several times that exploration wells located directly on bright spots resulted in dry holes. The failures may be associated with the fact that high energy reflections can be generated by not only the fluid content of the rocks but there are some other reasons connected with the wave propagation (e.g. constructive interference). Conclusions based on Hilbert-attributes and direct hydrocarbon indicators can be verified with the utilisation of Seislog technique and Amplitude Versus Offset (AVO) analysis. These sophisticated inversion procedures provide quantitative estimations for the petrophysical properties of the investigated geological model. Seislog sections (Lindseth 1976) are used to predict the acoustic impedance variations (the product of the wave propagation velocity and the density), and AVO analysis is performed to estimate the probability of the presence of fluid in the porous rocks (Ostrander 1984, Takács et al. 1999). These processes need more time and accuracy than simply computing the Hilbert-attribute sections, and they need a support of borehole geophysical data such as sonic and density logs.

A good example for the successful joint application of Hilbert-attributes, Seislog technique, and well log data is the reservoir characterisation performed by MÁELGI in the area of Szeghalom in 1986 (Figure 5.3). During that exploration, high-resolution information was provided about the inner structure of the reservoir, the petrophysical properties, and about the oil-water contact at some locations (Albu, Pápa 1992). Further production strategy of the hydrocarbon field was supported by all of this information.

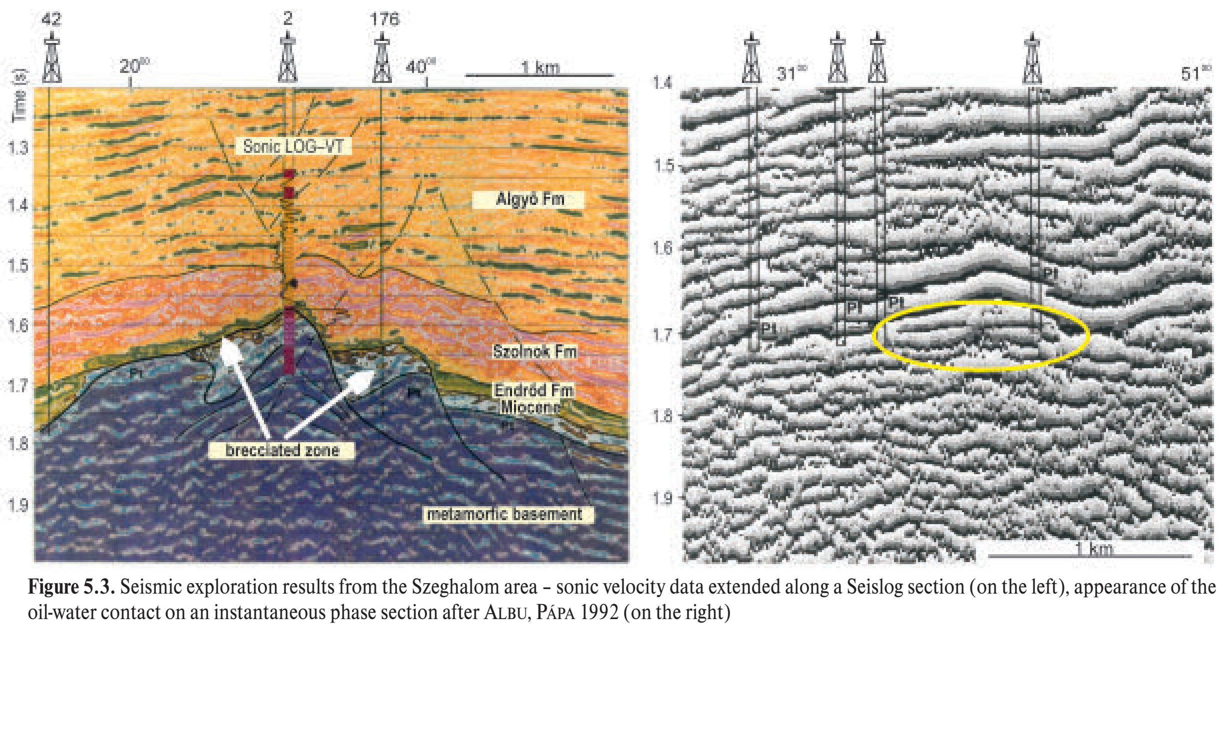

Figure 5.3. Seismic exploration results from the Szeghalom area – sonic velocity data extended along a Seislog section (on the left), appearance of the oil-water contact on an instantaneous phase section after Albu, Pápa 1992 (on the right)

It seems clear, that application of modern data processing and interpretation techniques outlined above was successful in the Hungarian petroleum exploration not just for mapping the geological and structural features, but also for lithological and hydrocarbon characterisation of the reservoirs of the Pannonian Basin; and utilisation of these techniques can lead to further successes.

Drilling, well test and well completion techniques

On the basis of completed geophysical and geological data gathered from different types of surveys, petroleum industry professionals allocate certain sites are supposedly above a hydrocarbon accumulation is willing to be drilled by an exploration well. Exploration wells are for a better understanding of an unknown geologic structure, while production wells are for the extraction of hydrocarbons from an already known accumulation.

In petroleum industry, *rotary drilling* is the most common drilling method and is used to drill both exploration and production wells. Rotary technology uses a sharp, rotating drill bit and downward pressure to cut, or crush, through the subsurface. The deepest Hungarian exploration well is below 6,000 meters deep in Makó Trough (M–7, 6,085m). In Western Europe within the German Continental Deep Drilling Program (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland), abbreviated as the KTB, borehole, a superdeep well for continental crust research purposes was drilled as deep as 9,010 meters in Bavaria, Germany. The derrick used at the site, one of the largest in the world, remains in place and has become a tourist attraction.

Basic rotary type drilling equipment are composed of rotating, drilling, mud fluid circulating, and casing equipment together with a blowout preventer system. Rotary drilling have evolved and changed in almost every detail over the past few decades. For minimising the environmental stress and the pollution emitted, a closed mud circulating system is the best option (Figure 5.4). In the past few years, light, easily transportable drilling equipment appeared (Figure 5.5).

Figure 5.4. Exploration well on the Alföld area

Figure 5.5. Easily transportable drilling equipment

Following requirements of our age, diesel-electronic engines are commonly used, as are natural gas or gasoline powered reciprocating turbines, which generate electricity on site and provide the power sources of drilling plants. 3–4 high performance (2,000–2,500 hp/engine) engines produce 600 V electricity, which is used to power the rig itself. The energy from these prime movers is used to power the rotary equipment, the hoisting equipment, and the circulating equipment, and on large rigs may be used as well to provide incidental lighting, water, and compression requirements not associated directly with drilling.

An alternative, newer surface drilling method is *top drive* technology, which includes a mechanical device on a drilling rig that provides clockwise torque to the drill string. The drill string is turned by mechanisms located in the top drive that is attached to the blocks, so there is no need for the swivel.

At rotary technology the static drill string does not provides rotation, it is just used for transmitting drilling fluids and torque to the drilling bit and the mud motor. Drilling bit is directly driven by the mud motor right above it or by a turbine using the flow energy of the transmitting drilling liquid, so it has an inner structure that is capable to use mechanical energy to rotate directly the drilling rig. This technology is mostly used at directional drillings, but also can be managed as an additional technique to top-driven drillings to enhance to drilling speed.

It is possible to penetrate rocks of different solidity; there are several types of drilling bits in common use. Two main

types of the drilling bits can be separated: first one is roller cone bits which crush the rock to obtain rock chips, other type is core driller bits where continuous cutting removal is possible to deliver continuous cores for further geologic and laboratory analysis, like in wireline coring. Rinse of the well is an essential element of a drilling operation, it is to lubricate and cool the drilling bit, mostly with drilling mud. Also, maintaining the hydrostatic pressure of the drilling mud ensures that fluid content of the original rock pores (water or hydrocarbons) would not be able to enter into the drilling hole, and also protects the well walls from collapse and flushes the rock cuttings from the hole.

For sake of protection of our environment, drilling mud is treated with special care of a closed technology (drilling technology without mud pit), special chemicals used during the process are harmless, debris of drilling mud and rock cuttings are controlled and the resulting waste (e.g. concentrated, dried mud, cuttings) is tested and transported to a dump site or official hazardous waste storage. Rock cuttings are sampled at certain depth intervals and after a careful stratigraphic investigation; ages of certain strata and sequences, as well as the lithologic column can be outlined. To refine these observations, wireline logging carried out with lowering a logging tool into the borehole to obtain information about the exact rock properties of the well.

To prevent wells from blowout, well control technique are used, which means that a valve is affixed to the wellhead operated with remote control, so the well can be capped at any time. A well control system aims to protect the well from the uncontrolled release of crude oil or natural gas, and is also used as a secondary defense system to keep water from being released when hydrostatic pressure of the drilling mud is not high enough. With careful controlling and planning, together with the absolute compliance of safety rules, most of the blowouts can be averted.

Completed wells have to be prevented from collapse and burst, and also have to be prevented from fluid mixing — which means different type of fluids, i.e. crude oil, natural gas and water situated in rock pores above each other with different hydrostatic pressure may migrate across the well —, so casing is placed into the well, which is a larger diameter pipe and usually fixed with cement to the well wall.

Directional or *slant drilling* means drilling of non-vertical wells. This technique is used in the following cases:

— if longer sections of the hydrocarbon-bearing strata or reservoir should be exposed to increase production; when drilling at an angle, the fluid content of the pores can flow into the wellbore from a larger area as the length of the section is longer,

— where vertical drilling is not possible, and the drilling has to be directed beneath a lake, a swamp, a town, a mountain, power plant etc.,

— if vertical drilling is not possible in a wildlife reserve, or beneath an agricultural area,

— if there is one main directional wellbore and several other bores are directed to the targeted object, i.e. the reservoir (directional drilling) or if there are several boreholes branching from the central site (bush-drilling) to expand the production,

— difficulties arise from the geologic features of the reservoir area, e.g. presence of salt domes, collapsing marl beds etc.,

— drilling a relief well, at a safe distance away from the blowout, but intersecting the troubled wellbore. Reaching the required depth, a heavy fluid (kill fluid, e.g. cement) is pumped into the relief wellbore to suppress the high pressure in the original wellbore causing the blowout. It took three months to repress the gas at the Pusztaszőlős gas blowout in 2000, where 130 million m^3 was lost,

— direct a dry wellbore into the reservoir,

— correct self-obliquity of a wellbore,

— due to economic reasons, it is less expensive to install less drilling rigs or grouped them together,

— rescue of a lost or damaged drilling object (Figure 5.6) or left in the wellbore for any other reasons.

From the very beginning (1944, Lovászi–94 well) until 2015, in Hungary 770 directional drilling were completed, with the greatest horizontal diversion of 1,299 metres at Szeged–4 wellbore. The greatest true vertical depth of a directional

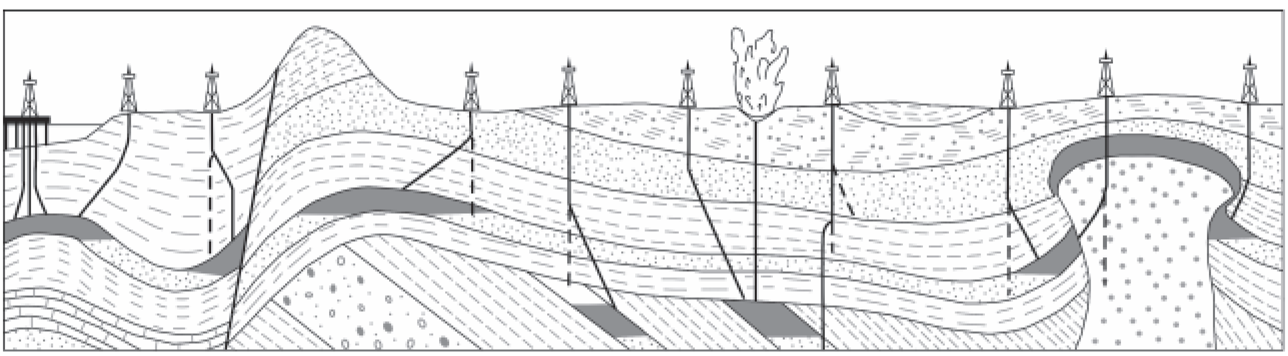

Figure 5.6. Sketch of types of directional or slant drilling (Ősz 2015)

wellbore was reached at the north-western part of the Makó Trough, at TXM Pusztaszer–1 exploration well at 3,784.8 metres, with a total length of 3,898 metres. It was necessary to drill with directional technique because installation of the drilling rig was only permitted outside the area of a nature reserve.

Conventional production tests were held in the wellbore after casing and cementing, after terminate the drilling. Its methodology and technique is determined by the structure of the borehole. Sometimes production tests can be managed with the original drilling equipment, but most of the times a smaller completion equipment so-called DST tool is used.

Production tests are run to obtain an indication of well productivity on the basis of presence and quantity of the pore fluids present in the reservoir, as well as to examine physical and lithological parameters of the reservoir related to the future petroleum production.

During a drill stem production test, the fluid content of the strata is tapped with the help of drilling equipment, while wireline surveys based on geophysical methods and use deep drilling geophysical equipment as production log, cable bit, cable, surface facility. Those strata, which cased and cemented properly, are ready to open — after completing certain geological and geophysical measurements on core bits and surveys — with perforation, and its aim is to allow the fluid content, including crude oil and natural gas of the pores of the reservoir to flow into the well. Perforation also is to provide effective flow communication between the wellbore and the reservoir.

In optimal case, natural hydrostatic pressure is enough to pump hydrocarbons on surface. In a case of a gas cap accumulation, the pressure of the gas above the oil, energy of the dissolved oil and the hydrostatic pressure of the water beneath the oil is enough to ensure the lift up with shriveling the oil from the pores. This is mostly specific for the early phase of the production. Well production lowers as the pressure decrease during the production continues, so the well needs stimulation to increase productivity again.

Permeability of the well area can be increased with the dissolving of certain, mostly carbonate-rich matrix which occludes the pores of the pool and obstructs the fluid extracting. These dissolving techniques are widely used in the petroleum industry since decades. *Acidizing* is a well stimulating technique to enhance decreasing well productivity, it has three main types. Intelligent acidisation is accessible nowadays, that let us to evolve various methods for high temperature environments and use liquid systems most suitable for the original mineral composition of the pool. Liquid systems used during these intelligent stimulations are partly natural acids which split due to the decomposing effects of temperature and time. Production from unconventional systems is managed from low permeability rocks or strata, from which would not been possible without *fracturing*. Its aim is to change the flow pattern of the reservoir, like in other stimulation methods. It is completed with high pressure fluid injections which open the target strata or rock, or, natural or synthetic grains of sand- or ceramics injected into the wellbore as a *proppant*, to avoid the collapse of the opened fracture. Hydraulic fracture is done with high performance hydraulic pumps. Water-based liquids applied during this method composed of ingredients used in the beauty-, food- and construction industry, and their regulation, permission and evaluation rules are included and fulfilled in the *Registration, Evaluation, Authorisation and Restriction of Chemicals*, REACH (USA). After completing the fracture, injected fluids were re-circulated into a closed pit system; they can be reused again or cleaned and deposited.

Subsurface parts of a production wells can suffer also mechanical failures after a certain time of production. Correction of all types of subsurface failures are summarised as well maintenance operations which include replacement of certain technical equipment within the case or the tube, their repair, or any kind of change, as well as cleaning and accumulation of contaminations and pollutions massed up during the production.

Well logging geophysical methods

It is possible, and most of the times necessary to make geophysical well logging, which can be managed during the drilling process or with its interruption throughout the open hole, or cased wellbore or competed boreholes as well. It is advised to obtain all the available information to be gathered together, including possible dangers and failures as well.

The LWD (logging while drilling) technique means the sensors are integrated into the drill string and the measurements are made in real-time, whilst the well is being drilled.

MWD (measurement while drilling) technique allows us to transfer parameters with pressure pulses in the well's mud fluid column to the surface during the continuing drilling process, as natural gamma-ray emission, porosity, resistivity, hole direction and vibration. More sophisticated MWD equipment is able to measure lithologic pressure and capable to gain samples from the sides of the hole. This equipment is attached to the end of the wireline cable, or they are separate parts of the drill floor or the setback, which are mainly playing role in directional drillings.

LWD systems may geophysical logging during the drilling process. The equipment is also the parts of the drilling rig, like MWD tools. Real-time LWD measurements can support making quick decisions like start a continuous core drilling, re-drill of a well or start the casing. But, the primary role of LWD data is to control and monitor the obliquity of the well and verification of different reservoir levels and beds. Besides, LWD data let us to allow correlate certain levels, detection of surrounding but not penetrated rock bodies, lithologic and physical parameters as porosity and petrographic structure of the

rocks, detection of potential hydrocarbon bearing zones or overpressured oil shales or crossing a fault zone. LWD technique is used most of the horizontal drilling and high obliquity wellbores against conventional geophysical well logging techniques. LWD technique can help us to specify prior information and let us to plan in more detail the deeper well geophysical loggings.

Geophysical well logging is used in petroleum industry since 1927. In the early years only electrical resistivity (RN and RG) and spontaneous potential (SP) have been measured, later other methods based on different physical approaches also have been involved into the logging.

A joint element of these different techniques is that the logging equipment attached to a special wireline cable and pulled down with continuous speed, therefore provides continuous, immediate and direct information from the drilled lithologic bodies along the wellbore. Result of the measurement is the log, which can be defined as an acquisition and summary of physical parameters of the formations' lithological and physical properties.

If geophysical logging is managed via wireline cables, then the drill string has to be removed from the wellbore, this means a pause in the drilling process.

Condition of the well can be detected on the basis of hole diameter and obliquity. Physical parameters of the penetrated rocks can be estimated via logging tools operating by different methodology. Cumulative interpretation of different logging tools let us to gain more information about the penetrated rock bodies: as their lithological parameters, porosity, permeability, hydrocarbon content, extension of the area infilled with drilling mud, rock density etc. It is possible to visualise the hole walls as a picture, so lamination, rugosity and fracturation can also be observed. According to the acoustic and seismic logging in the wellbore it is possible to correlate data with surface geophysical survey datasets. Rocks saturated with hydrocarbons can be tested from the well sides or it is possible to sample the fluid itself. Width and quality of the cement casing of the wellbore also can be examined, as well as its geometry and its possible damage. In production and infill wells, the technical parameters of the borehole wall and the lithophysical properties and hydrocarbon quantity changes during the production also can be observed.

Well logging first was operated in Hungary by Schlumberger Co in 1935, at Görgeteg–1 well. The Eötvös Loránd Geophysical Institute of Hungary (MÁELGI) managed its first electrical resistivity logging at Mezőkövesd–I borehole.

According to their physical background of the measurements, well loggings can be divided into two groups: the first group observes natural phenomena; the other large group detects physical characteristics connected to induced effects.

Parameters connected to natural phenomena:
— natural gamma ray activity (integral: GR, spectral: K, U, TH),
— spontaneous potential (SP),
— temperature (T),
— wellbore diameter (CAL),
— wellbore obliquity and azimuth (lithologic column, dip).

Parameters connected to induced effects:
— electrical logging,
— resistivity and conductivity (RN, RG, LL, ML, MLL, DIPMETER),
— induction (ILD, ILM),
— nuclear (induced with neutrons, or gamma rays),
— density: Compton effect (DEN),
— litho-(or Z-) density: photoelectric effect (ZDEN),
— hydrogen index, or neutron porosity (NN, NG, NPOR),
— macroscopic thermal neutron absorption effect (thermal neutron endurance TDT and/or NLL neutron endurance),
— acoustic logging (AC),
— longitudinal wave spreading time (VP),
— transversal wave spreading time (VS),
— Stonley-wave spreading time (ATST),
— full wave sonic (FWS),
vertical seismic profiling (VSP),
— acoustic borehole televiewer (BHTV).

The main tasks of well log evaluation are qualitative and quantitive geological interpretation based on the changes in physical parameters by depth. The shape of curves made of depth dependent measured physical parameters can refer to the superposition of different sedimentary phases, their duration, relative rate of sedimentary processes, unconformities, as well as results of tectonic movements. Another purpose of the evaluation is to calibrate some non-measurable parameters of certain rock bodies or beds via indirect observations, such as porosity, permeability, mud content, pore content, and composition, which parameters are calculated from empirical equations and also from field-laboratory observations.

Figure 5.7 shows an example of lithostratigraphic correlation based on geophysical well logging from a hydrocarbon exploration in the Battonya–Pusztaföldvár High. Curves are from natural spontaneous potential (SP), natural gamma ray

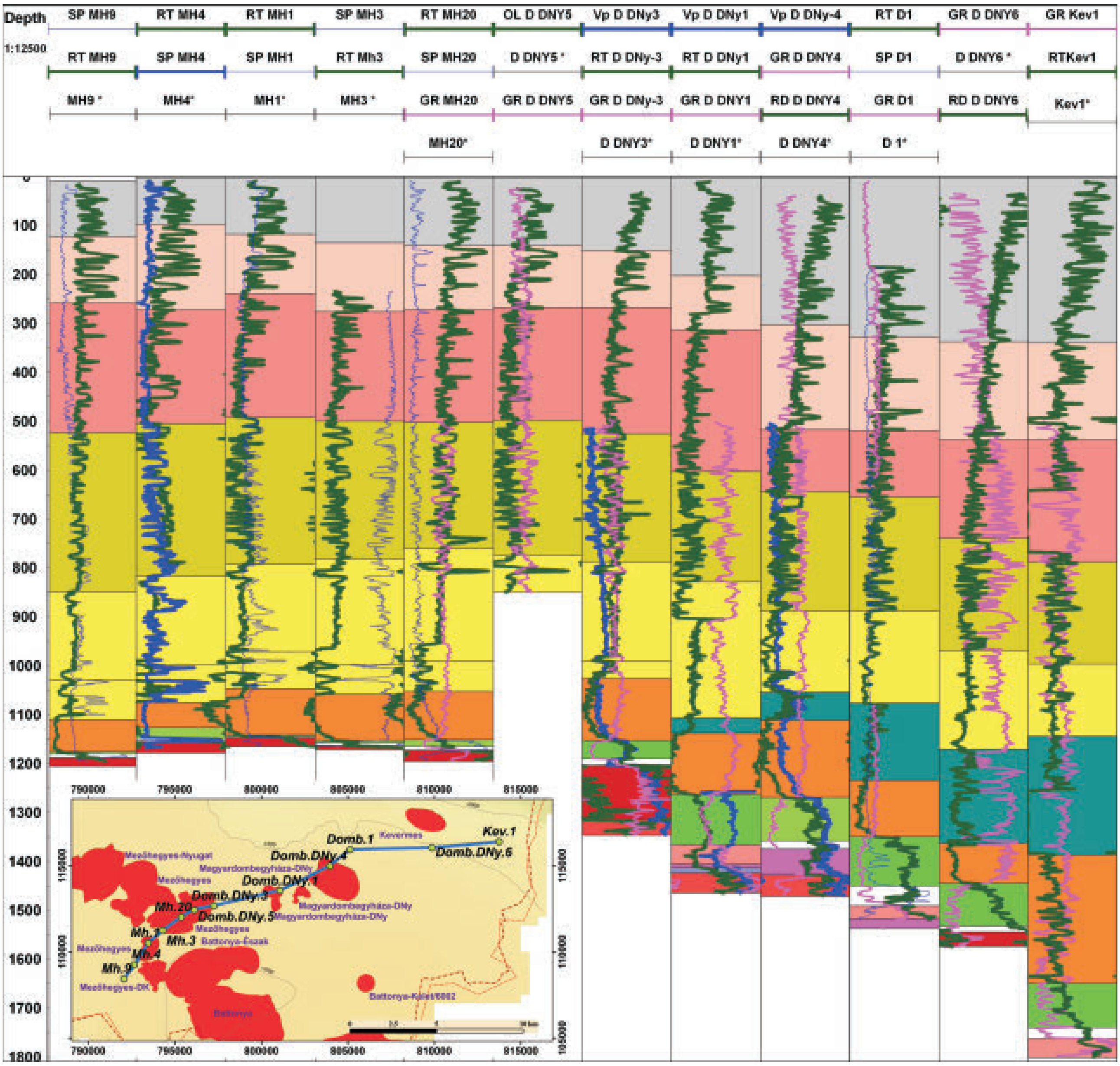

Figure 5.7. Lithostratigraphic correlation based on spontaneous potential (SP), natural gamma ray radiation (GR) and electrical resistivity (RT, RD, OL) well logs measured at the Battonya-Pusztaföldvár High area

Lithostratigraphic column is the following downwards: Quaternary, light pink: Nagyalföld Formation (Upper Pannonian), dark pink: Zagyva Fm (Upper Pannonian), greenish yellow: Újfalu Fm (Upper Pannonian), yellow: Algyő Fm (Lower Pannonian), bluish green: Szolnok Fm (Lower Pannonian), orange: upper part of the Endrőd Marl Fm (Lower Pannonian), green: Tótkomlósi Calcareous Marl member of the Endrőd Marl Fm (Lower Pannonian), white: Békés Conglomerate Fm (Lower Pannonian), pink: pre-Pannonian Miocene reservoirs, red, purple: Palaeozoic–Mesozoic basement

radiation (GR) and electrical resistivity measurements. Section from the Békés Basin upward to the basement high shows the pinching out of pre-Pannonian sequences, thinning of Pannonian base conglomerate (Békés Conglomerate Formation) and base marl (Tótkomlós Member of Endrőd Formation) towards the high, and the complete lack of the flysch deposit of Szolnok Formation on the top of the high.

Datasets are stored and saved electronically, which let us to process them electronically. Unfortunately, there are several well logs exist only in paper format.

These old paper well log maps can be converted to electronic form and are ready to use after digitalisation. The Mining and Geological Survey of Hungary keeps on continuously digitalising old paper-based well logs, together with their evaluation process.

Unconventional hydrocarbon occurrences in Hungary

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6

Introduction

In order to counterbalance the trend of the decreasing conventional reserves, foreign and domestic oil and gas companies have been paying attention to the exploration and production of unconventional hydrocarbons, predominantly tight gas and shale gas during the last decade.

Previously, in the 1990's, there were attempts to extract the methane content of the Jurassic black coal throughout well. Although the produced amount of unconventional gas is low in percentages compared to the cumulative production, the Government though decided to support unconventional explorations to enhance domestic petroleum production. By the amendment of Mining Act of Hungary in May 2015, the royalty of hydrocarbons from non-conventional sources, applying specific extraction procedures was defined in 2% in contrast to the former 12% that refers to conventional oil and gas. Concerning the technology of hydraulic fracturing that is need for the production of unconventional hydrocarbons Hungary has great experience gained along conventional hydrocarbon harnessing. The first attempts of hydraulic fracturing in Hungary are dated back to 1957 in the Zala Basin. There have been more than 2,000 cases where hydraulic fracturing was applied in conventional fields for well stimulation. The modern trials — targeting at shale gas and tight gas — started in 2006. In the Makó and Derecske Troughs there are continuously producing oil wells, although production faces several technical challenges due to the extreme thermal and pressure conditions related to the great depth of 3,500–6,000 metres of the occurrences. Hungarian Mining Act also defines notions and concepts on enhanced oil and gas recovery and unconventional hydrocarbon exploration and production, and encompasses provisions related to hydraulic fracturing techniques.

Related to the low permeability, so-called tight gas sands, Hungary has a great potential (Figure 6.1). According to the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of

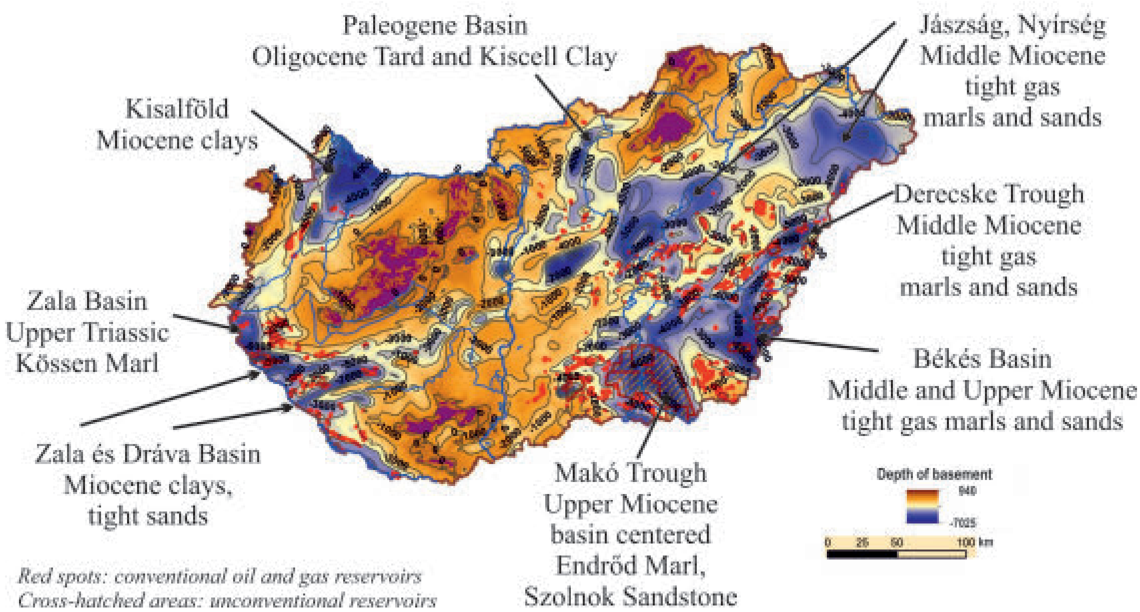


Figure 6.1. Basins with discovered and prospective unconventional hydrocarbon resources (shale oil, shale gas, tight gas) in Hungary (after KOVÁCS ZS., FANCSIK 2015)

Hungary (MBFSZ), based on the exploration reports of the mining contractors, unconventional recoverable gas resources is estimated 1,500 billion m^3, while gas recoverable condensate resources were estimated over 45 million tons.

These numbers are huge compared to the current 2 billion m^3 yearly domestic production of conventional natural gas, but production from unconventional accumulations was only 40 million m^3 until now, and it needs further investigations until the start of economic value productions.

There are 40 wells drilled for unconventional hydrocarbons, of which 10 wells were tested by hydraulic fracturing. On the basis of measured data the atmospheric and water emissions and the noise burden were below the national and the Community regulatory limits in case of these wells. No man-induced earthquakes were detected by passive seismic monitoring. The tests were performed in vertical wells, where inert proppants were used and clean water was used as fracking fluid

Unconventional hydrocarbons

Unconventional hydrocarbon systems also contain the basic elements and processes of the hydrocarbon systems, such as source rock, hydrocarbon generation, migration, reservoir rock, accumulation, trapping and seal or cap rock (Magoon, Dow 1994), but their volume, and partly their role can be different. As a result of that unconventional types of oil and natural gas or condensate (Law 2002) accumulations form.

Unconventional hydrocarbons can be defined on the basis of different point of views that are sometimes not closely related or even may contradict to each other (e.g. geological, economic or technological aspects). According to a rather clear, modern definition, every hydrocarbon accumulation must be considered unconventional, where separation of liquid phases (natural gas, crude oil and water) cannot be observed. Conventional and unconventional hydrocarbon accumulations may occur in the same geologic settings, sometimes close to each other with intermediate forms and strict boundaries may not be depicted between the two (Figure 6.2).

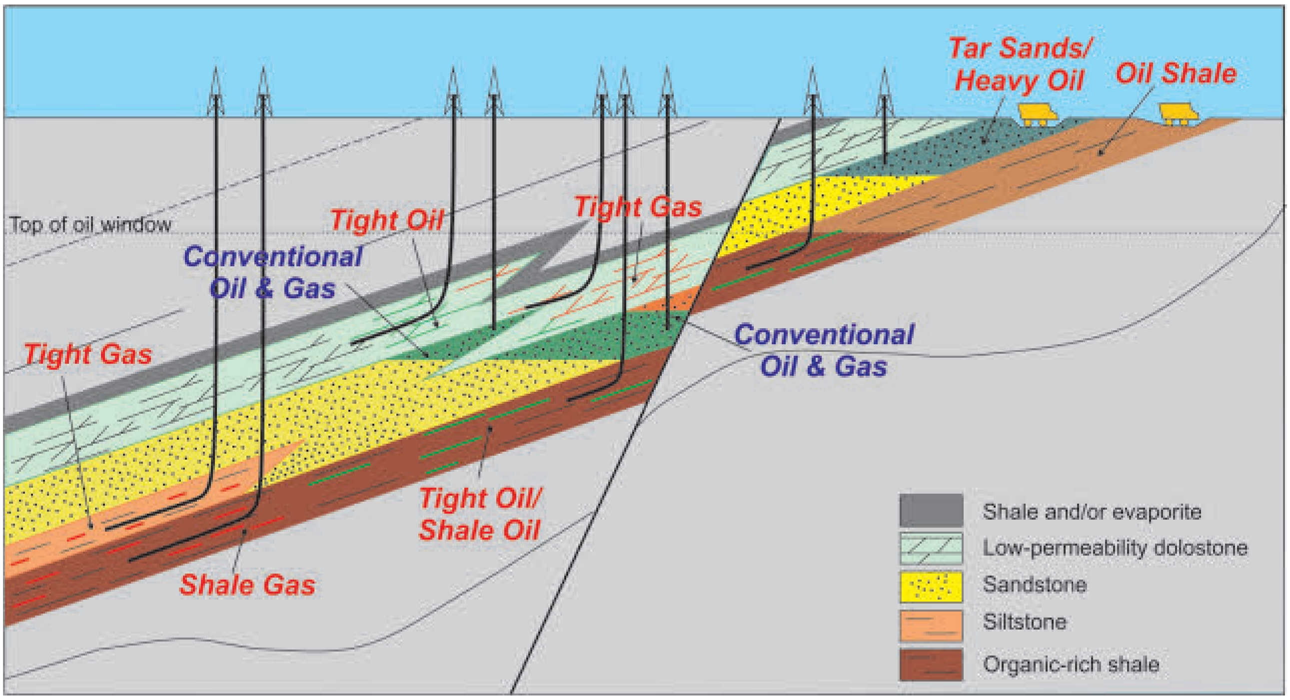


Figure 6.2. Conventional and unconventional hydrocarbons

There are two main groups of the unconventional hydrocarbon accumulations:

1) In the first group, secondary migration did not occur, so these are not hydrodynamic accumulations, i.e. the *originally generated hydrocarbons were stuck and trapped within the source rock*, and are characterised by very low permeability. There are no separated phases and observed phase boundaries, therefore productive rock volume cannot be defined: the source rock is the reservoir rock, which is in a state of continuous full saturation. From industrial point of view this means that at any point of the rock body natural gas, crude oil and water can be produced at a same time practically. In this case hydrocarbon production needs special processes as *hydraulic fracturing techniques* and use of *proppants* as fracture stabilisers.

2) The second type of unconventional hydrocarbons is those which were formed and accumulated with degradation of conventional hydrocarbon reservoirs by the dispersal or dissolution of the light or middle-weight fraction. In this case, the heaviest hydrocarbon compounds are concentrated as natural asphalts (bitumens) in tar sands (oil sands, bituminous sands), which cannot be extracted by conventional drilling methods, they can be extracted from the reservoir after steam, gas or dissolution liquid injections, or with surface mining methods and equipment. Their processing is held with two-stepped distillation technique where the original asphalt containing rock undergoes a dissolution or thermal process to extract synthetic hydrocarbons which finally goes through a refining process.

Conventional and unconventional hydrocarbon accumulations can be separated from geological point of view, which is visualised on Table 6.1, where contradictions related to terms "conventional" and "unconventional" are also pointed out. We speak about unconventional hydrocarbon accumulations as well if the hydrocarbon is not mobile, although original para-

Table 6.1. Conventional and unconventional hydrocarbons with a geological point of view, considering the flow capability of hydrocarbons and permeability of the reservoir rock

Hydrocarbon compounds	*Unconventional (cannot flow)*	Tar sands (extra heavy oil, bitumen, oil sand)	Methane hydrates, coal gasification/liquifaction, oil shale
	Conventional (mobile/flowable)	Conventional oil and natural gas	Tight oil, tight gas, shale gas, coalbed methane
		Conventional (porous and permeable rocks)	*Unconventional (mostly impermeable rocks)*
		Reservoir permeability	

meters, like porosity and permeability, of the reservoir rock would allow the mobilisation. Also it is true in reverse: an accumulation is considered to be unconventional if the originally mobile hydrocarbons were stuck or trapped in a reservoir, the parameters of which do not allow further migration.

Technology based approach is differentiated based on recoverability. According to this approach, an accumulation is considered unconventional if special techniques and methodology is needed to start hydrocarbon production: accumulations cannot be investigated without hydraulic fracturing, cannot be characterised homogenously by reservoir parameters, and cannot be produced automatically economically.

From a classical point of view, hydraulic fracturing is a productivity enhancing method, which is used for a geologically–geophysically well known, fairly well modelled productive reservoir as a stimulation technique to help hydrocarbons to flow more freely and usually this means greater yield. For unconventional accumulation, hydrocarbons cannot be produced at all without hydraulic fracturing. As an additional point of view, conventional–unconventional types of reservoirs are separated usually by their permeability, at 0.1mD (milliDarcy). From an economic point of view, it is to say that decrease in porosity and permeability of the reservoir rock means exponential increase of production costs (Kovács Zs., Fancsik 2015).

Exploration areas in Hungary

There are ten licenced assets for unconventional hydrocarbon exploration and production in the Mineral Raw Materials Registry, of which one is in the Nyírség area and the other nine are situated in the south-eastern part of the Great Hungarian Plain (Alföld) (Figure 6.3). In these areas, the presence of unconventional tight gas in low permeability sandstones was proved by exploratory wells.

The registered amount of discovered resources which were initially in-place, discovered recoverable resources and the total production of unconventionals are shown on Figure 6.4. Coalbed methane is not included in this figure.

The Great Hungarian Plain is the most prolific oil and gas producing area of Hungary, currently is the main target area of unconventional hydrocarbon explorations as well. In the Makó Trough (Mindszent, Makó, Makó Trough–I, Hódmezővásárhely exploration areas) Late Miocene, Pannonian tight gas, gas condensate and shale gas, in the Kiskunság (mining

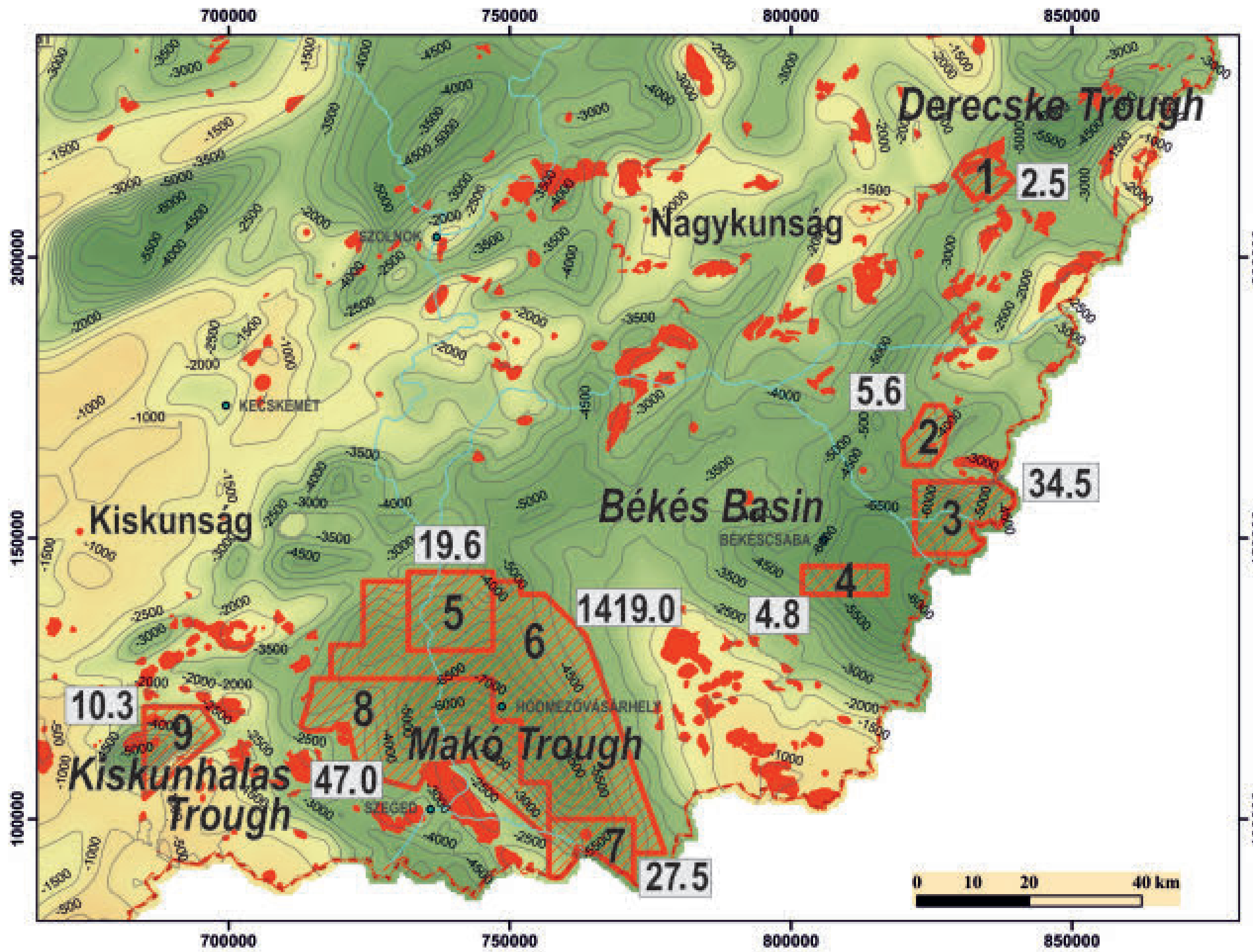


Figure 6.3. Unconventional discovered recoverable resources in billion m3 in the south-eastern part of the Great Hungarian Plain (according to the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ)

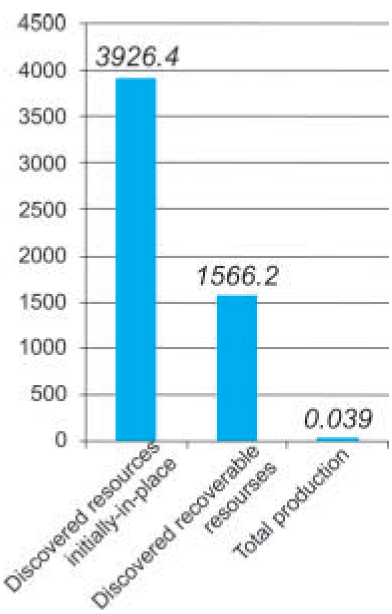


Figure 6.4. Registered unconventional hydrocarbon resources according to the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ) of January 2016

site of Balotaszállás) and in the Békés Basin (mining site of Szabadkígyós, Gyulavári and Nyékpuszta), and in Derecske Trough (mining site of Berettyóújfalu) Miocene tight gas are under exploration and production testing.

In the Zala Basin of SW Transdanubia, unconventional shale oil is connected to the Triassic Kössen Marl Formation. In the Lenti and Letenye areas in the Dráva Basin, Miocene tight gases are considered as a possible exploration potential. It is supported by the hydrocarbon exploration being carried on at the Croatian part of the Dráva Basin, and in the Slovenian side of the national border, where the drilling tests refer to remarkable recoverable amounts of hydrocarbons from Middle Miocene tight sandstones.

Due to their intense maturity and tectonic position, exploration of the Lower Jurassic marls in 500–1,600 metres depth in the north Mecsek area, as well as in the Kiskőrös, Nagykőrös areas of Duna–Tisza Interfluve area and in the vicinity of Ebes in the Tiszántúl (left side region of the Tisza River in the eastern part of Hungary) also suggest available unconventional hydrocarbon potential.

In the north-west part of the country, in the Danube Basin (Little Hungarian Plain, or Kisalföld in Hungarian) mostly CO_2 gas occurrences are known, although it is a potential area for unconventional hydrocarbon exploration, direct exploration workouts have not been started yet.

There are several conventional crude oil and natural gas fields known in the Hungarian Palaeogene Basin, unconventional accumulations of shale oil in Oligocene shales and marls (Buda Marl, Tard and Kiscell Clay Formations) are also prospective targets.

In Hungary, the occurrence of oil shale has long been known: alginites have

been found in several parts of Transdanubia (eg Pula, Gérce). Kerogens, an organic compound which hydrocarbons are generated from alginites, and usually other types of oil shales, are thermally immature. Hydrocarbons can be extracted from them only after a very expensive distillation process. Compared to the economically producible unconventional oil shale produced wordwide, the production of alginites, due to its restricted resources, cannot be made commercial even if the market price of oil rises much higher than it is at present. Therefore, the use of the alginites for agricultural and environmental purposes seems more reasonable.

Methane content of Mecsek black coals is also remarkable. Evaluation of the domestic coalbed methane (CBM) resources is included in a study of 2012 "Report on the evaluation of hydrocarbon potential to support the national mineral resources utilization plan" (HÁMORNÉ VIDÓ, PÜSPÖKI in KOVÁCS Zs. et al. 2013), figured on Table 6.2. Amount of CBM is not included in the unconventional hydrocarbon resources of National Mineral Raw Materials and Geothermal Energy Resources Registry of Hungary.

Table 6.2. Domestic coalbed methane resources, estimated on the basis of mining data

Coal basins	Specific methane content (m^3/tons) (FODOR 2006)	Data of dewatering (m^3/min)			Prospective coalbed methane resources in-place (billion m^3)*
		min.	max.	mean	
Mecsek	50*	0	5	2,9	143**
Dorog–Pilis	5–10	0	100	21	2–4
Tatabánya–Nagyegyháza–Mány	8–12	0	132	29.6	3–5
Oroszlány	2–3	0	1	0.4	0.3–0,5
Bakony (Eocene)	1.3	0	10.5	7.5	0.2
Bakony (Cretaceous)	2	0	18.8	11.1	0.7
Várpalota (Miocene)	1–1.3	0	15	5.5	0.3–0.4
Nógrád	6–12	0	2	0.5	1.3–2.5
Borsod and Ózd area	1–2	0	9	3.5	1.1–2.3
North and West Hungarian lignite areas	no data	0	40	22.3	no data
Total resources					151.9–159.0

* Methane quantity released by mining.

** Coal mine methane (CMM) can be produced in case of 2 million tons/year coal production, max. 100 million m^3/year capacity.

Surface occurrences of natural asphalt, tar sand and bituminous sand are not known in Hungary, accumulations of gas hydrates are excluded as well due to their specific formation environment.

Amount of shale gas and tight gas can hardly be estimated due to the lack of information gained from detailed unconventional hydrocarbon explorations, also difficulties in successful production of the occurrences in the Great Hungarian Plain related to the geological background and thus technical shortage (that probably will not be eliminated in a few years). The situation is similar related to the coalbed methane accumulations known from the Mecsek area, where the discovered CBM resources are much more than conventional natural gas, but its production technique and methods are not well developed yet.

Makó Trough

There were some indications of combustible natural gas in Mindszent–1 well drilled in 1964–65 in the area, where the gas was accumulated in sandstone bodies characterised by high formation pressure (KŐRÖSSY 2005a, b). In Makó-1 well drilled in 1969, Szolnok Sandstone Formation produced a small amount of combustible natural gas and 3.2 m^3/day condensate during exploration tests. Based on seismic interpretation data, the National Oil and Gas Trust (OKGT) installed the Hód–I well near to Hódmezővásárhely, at the deepest part of Makó Trough in 1969–1972, which was planned to reach 6,000 metres depth. Due to technical difficulties it stopped at 5,842.5 metres depth, and became Hungary's most well-documented exploration well (pl. BÉRCZI, PHILLIPS 1985, ROYDEN, HORVÁTH 1988, SAJGÓ et al. 1988). A slight indication of combustible natural gas was only observed from the Upper Miocene (Lower Pannonian) Endrőd Formation.

Makó–2 well drilled in 1974 and reached 5,060 metres depth, showed indications of combustible natural gas and gas condensate and proved the presence of unconventional gas in Szolnok and Endrőd Formations. Base of the clay-bearing sandstone reservoir is at 5,500 metres depth; its top is at 2,300 metres according to seismic reflection sections and well loggings. Average porosity of the reservoir is 2.5%, combustible part of the natural gas is 94%, its calorific value is 35.8 MJ/m^3, its methane content is 79%, the CO_2 content is 4%, the N_2 content is 2% according to the data of the National

Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ).

There was natural gas indication observed in Endrőd Formation of Sándorfalva (Sánd)–I well drilled also in 1974. In Makó–3 well drilled in 1987, a 2.6 m^3/day light oil indication was observed besides water and combustible natural gas inflow during formation tests. Majority of the wells drilled since the 1970's were proven dry in the areas of Baks, Mindszent, Felgyő, Szegvár and Apátfalva (e.g. Mindszent–2, Felgyő–I, Szegvár–V and –VI), and also there were only slight gas indications in Felgyő-SE–1 well (HATALYÁK et al. 2006, GYARMATI et al. 2000). Exploration activity of the Mol Hungarian Oil and Gas Plc in the Makó Trough and its surroundings was concentrated mainly to Csongrád–Mindszent (GYARMATI et al. 2000), Mindszent (KISS et al. 2010b), Makó West (HATALYÁK et al. 2006) and Szeged Basin (KISS et al. 2010a) areas. Since 1998, an American petroleum company, the Gustavson Associates Inc 2003, as well as their Hungarian branch office, later since 2005, the TXM Oil and Gas Exploration Co connected to a Canadian petroleum firm, Falcon Oil and Gas Ltd explored the area of Makó Trough. They have been completed several 2D and 3D seismic measurements, in Pusztaszer, Hód North, Makó West, Székkutas and Gátér sub-areas.

At the north-western edge of the Makó Trough, Pusztaszer–1 well was drilled to explore conventional and basin centered gas accumulations (Figure 6.5). This well produced 7,079 m^3/day natural gas from the Szolnok Sandstone Formation. TMX Co drilled several wells between 2006 and 2007: at the deepest, central part of the Makó Basin Makó–4 and –6 and a record of 6,085 metres depth of Makó–7 wells were installed, while at the edges of the trough were explored by Székkutas–1 and Magyarcsanád–1 wells. There were mineralogic, petrographic, biostratigraphic, organic geochemistry, lithomechanical and petrophysical researches carried out on the cores (e.g. UNGER et al. 2007), and on the basis of these data numerical modelling was completed as well (HORVÁTH et al. 2010). Syn-rift deposits and basal conglomerate at Makó–6 well produced 19,822 m^3/day natural gas.

The Székkutas–1 well produced 42,475 m^3/day natural gas from Szolnok Sandstone Formation, the Magyarcsanád–1 well produced natural gas of 28,316 m^3/day besides gas condensate from the Endrőd Formation. Until 1st of January, 2012, Makó–6 well produced 7,760 m^3 natural gas, Magyarcsanád–1 well produced 334,477 m^3 natural gas and 64.33 tons of gas condensate. Average thickness of the reservoir rock is about 3,000 metres; its average porosity is 6%. The density of the condensate is 760 kg/m^3, its calorific value is 37 MJ/m^3, the methane content is 57.1%, CO_2 24.3%, and N_2 4.4% according to the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary (MBFSZ).

Mindszent–3 and –3/a exploration well of 3,860 metres depth drilled by the Mol Hungarian Oil and Gas Plc in 2008 had gas indications, but during the production test beside the strong hydrocarbon indication, a massive water inflow occurred. Due to emerging technical problems caused by the high overpressure, the drilling was temporarily abandoned before it could reach its final planned depth. In this well, three unconventional natural gas accumulation zone settled to each other were identified in Pannonian reservoirs (KISS et al. 2010b). Natural gas is captured in Upper Miocene Lower Pannonian sequences of Szolnok and Endrőd Formations in silty sandstone and is not related to any structural trap. Combustible part of the gas is 94.0% in average, its calorific value is 39.0 MJ/m^3, with a methane content of 81.4%, the CO_2 is 5.9%, the N_2 is 0.1%, the C_{5+} content is 27 g/m^3 according to the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary.

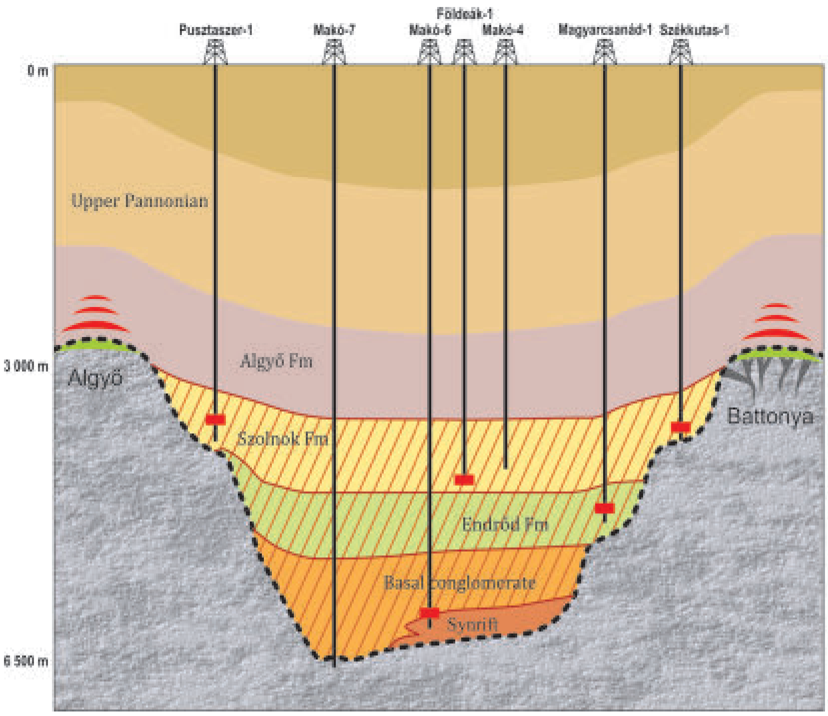


Figure 6.5. Locations of hydrocarbon occurrences in the Makó Trough and its surroundings. Hydrocarbons are coloured red (after Falcon Oil and Gas Ltd, http://www.falconoilandgas.com/mako-hungary)

In 2009, one of the greatest petroleum companies, the Exxon Mobil also completed exploration drilling in the area (Figure 6.6), which were mostly targeted unconventional basin centred gas accumulations. Consortium of Exxon Mobil, TXM and Mol completed a joint project on drilling of Hódmezővásárhely–1 (Hód–1) and Földeák–1 wells. Hód–1 reached 4,351 metres total depth, and during the first period of

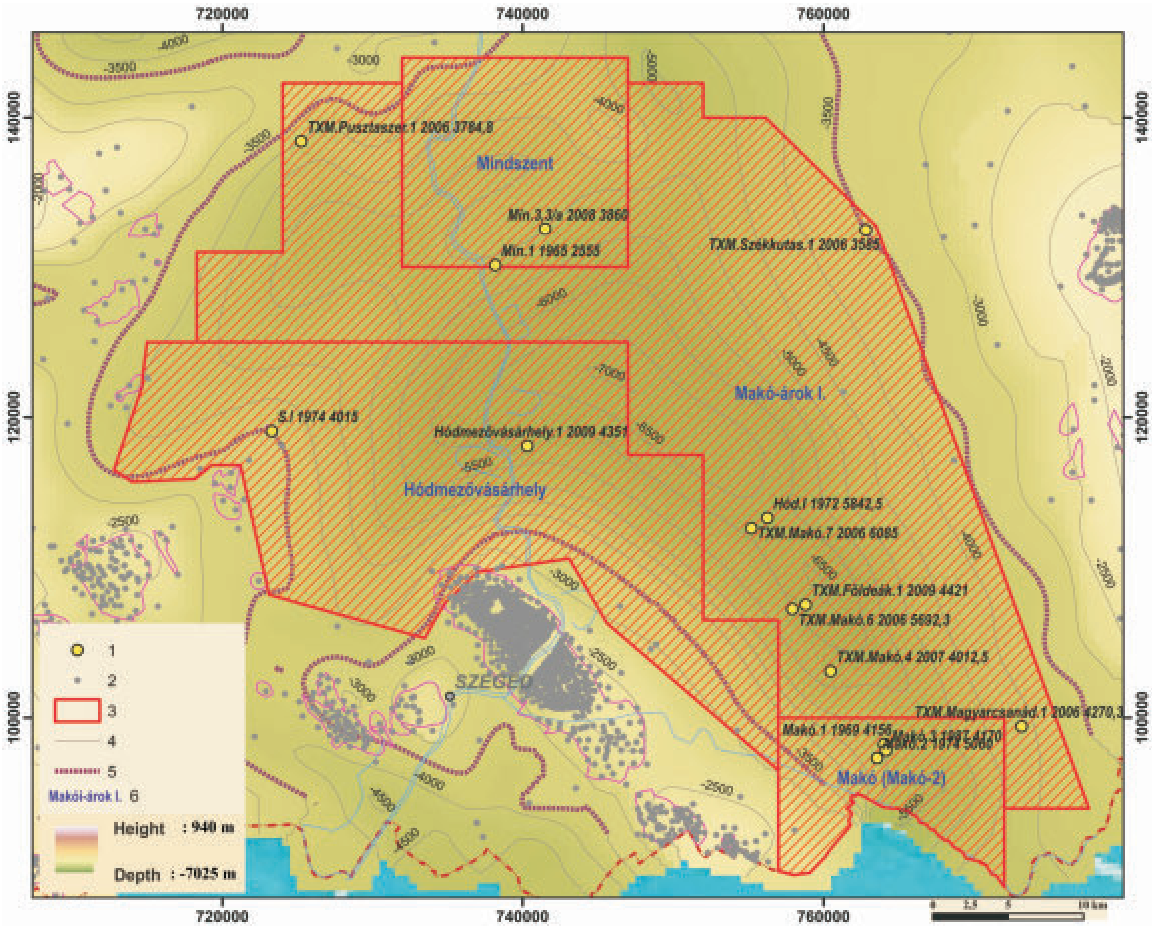


Figure 6.6. Exploration wells and unconventional hydrocarbon accumulations of the Makó Trough

Legend: 1. exploration well reached at least 3,500 metres depth, 2. other hydrocarbon exploration wells, 3. Unconventional mining site, 4. depth of the pre-Cenozoic basement, 5. contour of 3,500 metres bsl approximate top of the overpressure zone, 6. relief map of the pre-Cenozoic basement

production tests it produced 11,000–14,000 m^3/day, then 3,100–3,700 m^3/day natural gas, and confirmed the presence of pervasive gas saturated accumulations at the lower parts of Endrőd and Szolnok Formations. Combustible part of the natural gas was 91.8, its calorific value was 39.0 MJ/m^3, its methane content was 81.8%, the CO_2 8.1%, the N_2 0.1% according to the MBFSZ. In total 32,289 m^3 natural gas was produced from Földeák–1 well.

Basement formations of the Makó Basin were suitable for hydrocarbon generation only in very limited extent (Kőrössy 2005a, b). Mesozoic rocks of the Makó Trough basement are situated in very restricted areas and deposited in very limited width mostly not in anoxic environmental conditions. However, among the Neogene formations the deep marine Badenian and deep lacustrine Lower Pannonian clays and calcareous marls are of great extension and of huge organic content are potential source rocks. Based on measurements carried out on their organic content (Horváth et al. 1988; Szalay 1988; Sajgó et al. 1988; Hetényi et al. 1993; Clayton, Koncz 1994a; Clayton et al. 1994a, b; Koncz, Etler 1994; Badics et al. 2011a, b; Badics, Vető 2012), the Pannonian Endrőd Marl Formation is proven to be as a source rock, Algyő Formation and some among Badenian and Lower Pannonian synrift deposits also can be treated as potential source rocks (such as Makó member Badics et al. 2011a, Figure 6.7).

According to investigations based on the most important features and parameters of source rocks like width, total organic content and hydrogen index, Badics et al. (2011a) estimated 490–650 billion m^3 natural gas accumulations in total in the area of Makó Trough. The quantity of accumulated crude oil is very uncertain, approximately 100–200 million m^3, some of which may have been migrated upward, but about 20–30% could be left in place and cracked. In the authors' opinion, that huge amount of natural gas was unlikely to be generated in the Makó Trough which is supposed to fulfil all the pore volumes of reservoir rocks of Endrőd and Szolnok Formations and thought to be form a basin-centred gas accumulation. Gas saturation of sandstone successions on the basis of some well loggings at Fábiánsebestyén–4, Makó–3, Hód–1 wells is low, which accompanied by free water saturation that led to unsuccessful hydrocarbon production even after hydraulic fracturing (Badics et al. 2011a).

The Makó Trough is proved to be prospective in terms of regional basin-centred gas accumulation from an unconventional hydrocarbon explorational point of view, but our limited geological and geophysical knowledge besides restricted

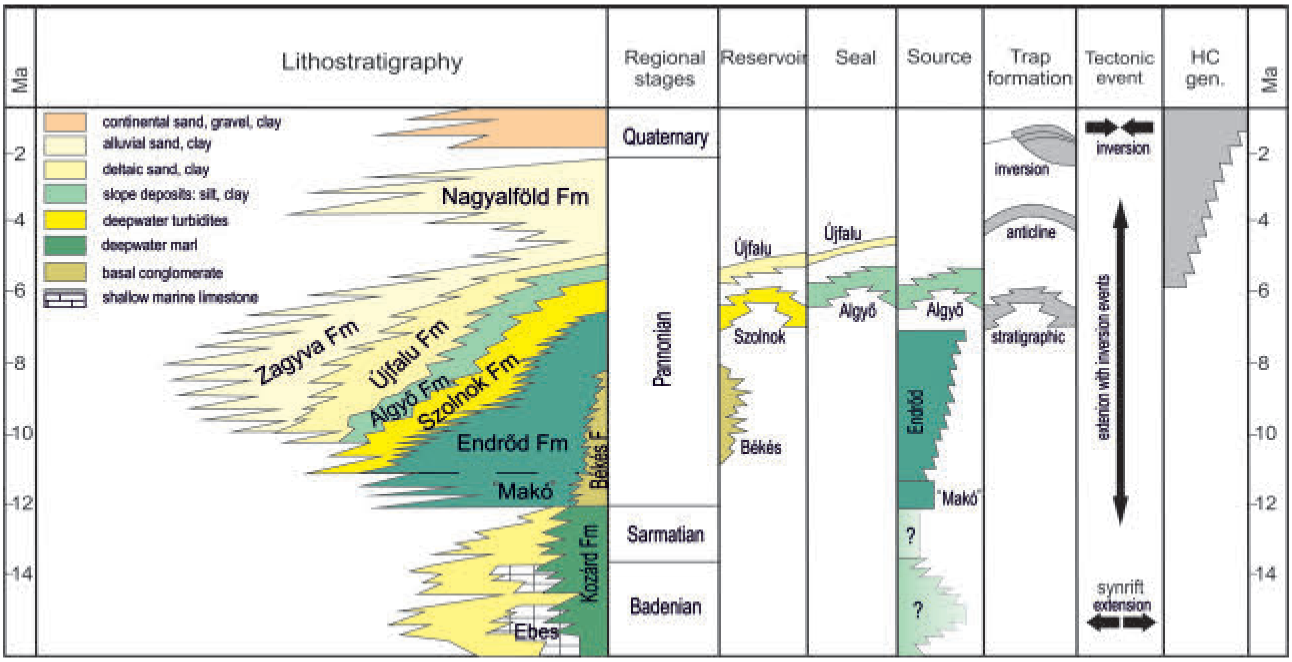


Figure 6.7. Neogene elements of the hydrocarbon system of Makó Trough (after BADICS et al. 2011a)

numbers of deep wells reached at least 4,000-6,000 metres depth make the discovered unconventional resources to be concerned as contingently recoverable and of high risk.

Derecske Trough, Berettyóújfalu occurrence

Mol Hungarian Oil and Gas Plc has drilled 5 deep exploration wells (Beru–1,–2,–3,–4,–6) beyond 3,000 metres between 2005 and 2011 in the area of Derecske–Berettyóújfalu–Földes to reach and explore the extremely thick Lower and Middle Miocene formations for the purpose of natural gas production.

Unconventional tight gas accumulation of Berettyóújfalu is situated in the south-west part of the Neogene Derecske Trough. The depth of the trough with NE–SW strike vary a lot: Beru–1 and –2 wells situated in marginal position reached the basement at 3,560 metres depth, while seismic data suggest the basement depth at the deepest part below 4,600 metres.

The basin is filled with Miocene siliciclastic and volcano-sediment sequences overlain right to the top of the Palaeozoic rocks in 300–700 metres thickness. On the top of these formations a 2,500–2,800 metres thick Pannonian sequence deposited with a slight hiatus, and it also covered by an approximately 500 metres thick Pliocene–Quaternary sediments (Figure 6.8). The almost complete sedimentary succession represents the continuous subsidence of the basin.

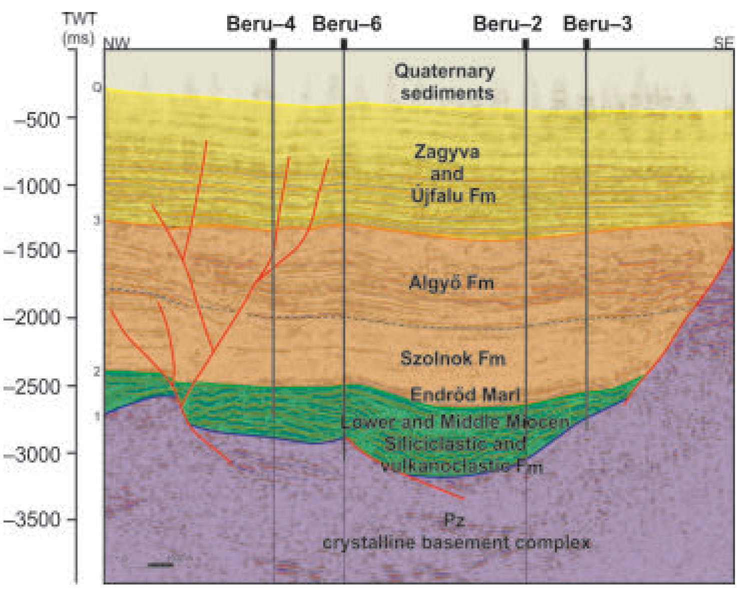


Figure 6.8. A NW-SE oriented geological section through the Derecske Trough (NÁDOR et al. 2016)

Source rock: On the basis of its average TOC content that is usually at least suitable (1–2% TOC), the generally prevailing Endrőd Marl Formation explored from Beru–1 core samples did not show any features of a source rock. The Miocene sequence contains intercalated strata of source and reservoir rocks between 3,471 and 3,616 metres in Beru–4 well. The upper part of the sequence (M2) contains 43%, the lower part (M–I) contains 28% of source rocks, mainly in a form of terrestrial and marine pelitic sediments.

In terms of TOC content the source rock is rated at least appropriate on average, good in the

lower part, excellent (8–10%) on the upper part, and its organic material consisting of type III kerogen, which is suitable for generation of natural gas and crude oil, as well. (Szentgyörgyiné et al. 2012b).

Nevertheless, comparative analysis of organic content of different wells shows that similarities in lithofacies do not automatically indicate similar organic content (as different quantity and quality source rocks compose the hydrocarbon system). According to 3D seismic survey data, potential source rocks are highly thicken towards the depocenter of Derecske Basin.

Thermal maturity: Thermal maturity of the source rock, based on Rock-eval pyrolysis on cores and cuttings of Beru–4 well, can be placed into the generation zone of crude oil – wet gas, while vitrinit reflectance data suggest a maturity state close to the end of oil generation. Difference can be explained by the long-lasting heavy overpressure which resulted in lower vitrinit reflectance value of 1.1%. According to calculations, Middle Miocene source rocks reached the thermal maturity suitable for oil-window approximately 7 million years ago, while Upper Miocene and Lower Pannonian source rocks started to generate hydrocarbons at their earliest 6.5 million years ago, or they are still immature yet (Szentgyörgyiné et al. 2012b).

Migration: Lateral migration is minimal and restricted also vertically in the rocks which are sources and reservoirs all together. This is caused by the joint effect of the low porosity and permeability and the overpressure caused by compaction, which can be as high as 60–80% in Middle Miocene formations. In the Miocene lithologic and facies changes, early diagenesis and forming of faults may led to the development of migration barriers, which cause a segregation in sediments also manifested in differences of hydrocarbon composition. This can be the explanation as well for the fact, that between bodies with different gas-composition there is no vertical transition zone, just absolutely depleted zones can be traced. So it is possible to follow easily as the maturity and/or the organic facies of the source rocks vary laterally and vertically.

Trapping: Main seal rock formations are the regional impermeable clayey beds between the Middle Miocene siliciclastic and tuffaceous successions, as well as the Upper Miocene Endrőd Marl Formation and the overlying fine-grained, clayey lower parts of the Szolnok Formation, all of that ensure regional seal. Important factors in trapping are the lithology, the compaction and capillary closure due to diagenesis, as well as the presence of faults.

Beru–1 to Beru–6 wells drilled gas containing formations within the basement, the pre-Pannonian Miocene and Pannonian successions as well. Unconventional accumulations divided into four reservoir levels with seven assessment units were determined.

Reservoirs of siliciclastic Middle Miocene sequences in deeper stratigraphic position (Beru-M–I), and a tuffaceous volcano-sediment reservoir sequence (M2 unit) in its overburden, are basically different. Different sedimentary successions were recognised in the two sides of the trough as well by the exploration wells, so the discovered reservoirs were referred as independent units. Reservoirs could be pinched out within the Derecske Basin. There is no mobile water in the pores, or its quantity is minimal, no real segregation was held due to the poor permeability, there is no gas-water contact evolved in the reservoirs.

On the north-eastern side of the trough, three accumulations of Beru-M–I unit explored by Beru–1,–4,–6 wells contain natural gas of 39.5 MJ/m^3 calorific value, its combustible part is 90–97%. Its methane content is 75%, CO_2 varies between

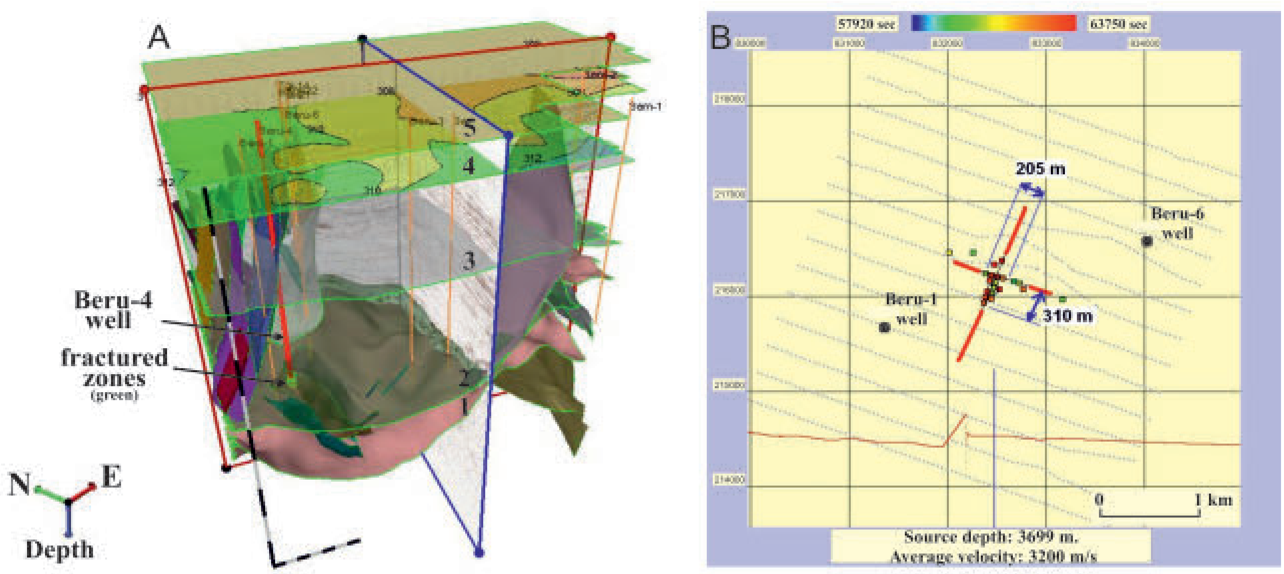


Figure 6.9. A) 3D geologic model of Berettyóújfalu accumulation showing the relevant sequence boundaries (model layers) and tectonic surfaces, and the extension of hydraulic fractured zone (coloured in light green) in Beru–4 well. Scale bar represents 500 metres (Nádor et al. 2016) B). Detailed map shows a plain view of microseismic events detected in 3,700 m depth in the surroundings of Beru-4 well, as well as visualize the fracture system geometry initiated by hydraulic fracturing (after Zsellér 2012)

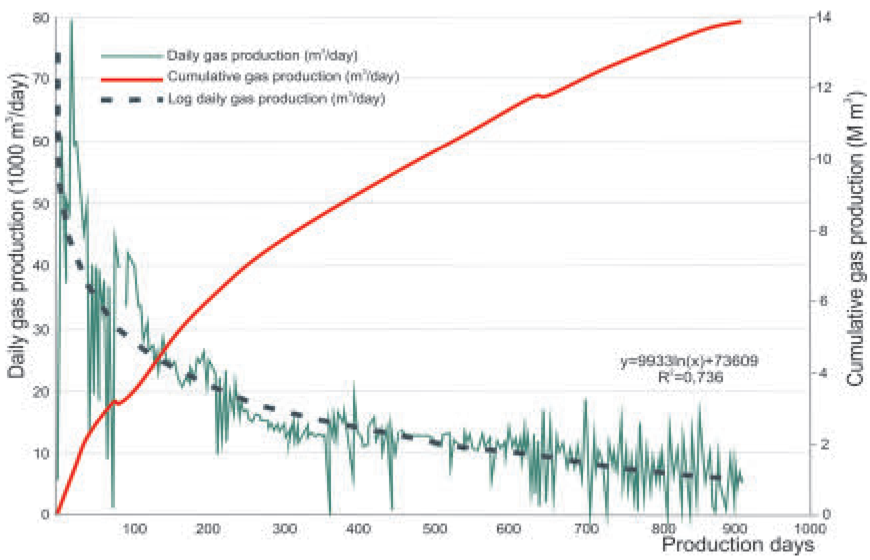


Figure 6.10. Production data from Beru-4 well (after KISS 2015)

0–8.8%, N_2 varies between 0.2–2.9%, the C_{5+} content is between 10–30 g/m³ according to the register of the Mining and Geological Survey of Hungary. Exploration tests in Beru–1 well show an environment characterised by high pressure (57.1 MPa) and high temperature (200 °C), with an average porosity of 8% and average permeability of 0.07–0.09 mD. Thermal gradient is 0.053 °C/m.

Accumulation, named Beru-M unit (and Beru-M2 and Beru-6–M reservoirs) located also at the NE margin of the trough, has better porosity, with an average of 12–14%. Its combustible part 77% in average, their calorific value is of 29.9 MJ/m³. Their methane content is 69–76%, CO_2 varies between 6–22%, N_2 varies between 0.2–0.4%, C_{5+} content is between 20–50 g/m³ according to the register data of the Mining and Geological Survey of Hungary.

Two separated gas reservoirs explored by Beru–2 and Beru–3 wells located on the SW margin of the trough, contain 87.2% combustible gas, its calorific value is 31.3 MJ/m³. Average porosity is 5%.

Hydraulic fracturing: first production tests of Beru–1 well without stimulation show rapid pressure change by low yield that suggests the presence of tight gas, from which the production is not economic without hydraulic fracturing. Currently the well is just temporary produced. In the subsequently drilled Beru–4 well 3 gas containing zones was hydraulic fractured. The process was continuously monitored by microseismic observation, from which the geometry of the fractures, therefore the possible migration routes and relationships between routes of contaminations, the quantity of released energy and so the induced seismic risk of the hydraulic fracturing process could be concluded (NÁDOR et al. 2016).

Dimension of fractured zones are between 60–65 metres in height and 90–130 metres in half length (Figure 6.9). In 2012, Beru–4 well was prepared to turn in production, and the well intervention/reinjection-formation test-production has been started, which results are visualised on Figure 6.10.

Békés Basin

Although Békés Basin is explored by more than 700 hydrocarbon wells, the deepest basinal areas of reached by hardly a dozen of wells as Békés–1, –2, –3, –4, –5; Doboz–I; Örménykút–I; Hunya–1; Kőröstarcsa–I, –1; Kondoros–1; Gyoma–1. However, these few wells provided us most of the information on the geological potential of unconventional type basin centred gas accumulations (BCGA) in a low porosity reservoir.

Recently, Mol Hungarian Oil and Gas Plc (on the Szabadkígyós exploration area) and Hungarian Horizon Energy (Magyar Horizont Energia) Ltd (in Túrkeve–Vésztő, Elek–Lökösháza and Gyomaendrőd–Tarhos–Gyulavári exploration areas) have been carried out with unconventional hydrocarbon exploration, which served as a base for the settlement of Gyula–I and Gyula–II unconventional hydrocarbon mining sites, as well as the Sarkad–I hydrocarbon mining site covering the a Nyékpuszta–1, –2 unconventional hydrocarbon fields. The BCG zone can be found at approximately 3,000–5,000 metres depth, and can be characterised by the following (according to the Hungarian Horizon Energy Ltd, MHE 2010):

1) A young succession which has not reached its equilibrium in terms of compaction, and contains thick clayey intercalations, so a certain percentage of the pore water was not able to migrate from the sediments; its gas content is in a partly dissolved state in water, with migration of pore fluids determined by relative permeability.

2) Due to the high thermal flux and high geothermic gradient, processes of compaction, hydrocarbon generation and hydrocarbon migration are very close to each other in relative time, so mixed compaction phase formed with the presence of pressure barriers, therefore isolation and formation of the BCG zone had been started relatively early.

3) Young tectonic movements did not caused inversion, but opened significant migration pathways for hydrocarbons, so the escape of catagenetic gases was able to happen and hydrocarbon accumulations had been formed along the margins or above the BCG zone, as well as inert gases migrated into the Miocene sequence of the BCG zone. The system, open from the basement, resulted downward migration, which allowed further migration for its hydrocarbon content along the Neogene/Palaeozoic–Mesozoic unconformity surfaces towards the margins of the basin.

4. Two overpressured systems can be separated within the BCG zone. The upper one can be characterised by mixed compactional facies with local migration pathways, with significant pore water movement, and with conventional and unconventional hydrocarbon accumulations. The lower one is a massively overpressured system with coarse-grained siliciclastic beds embedded within thick clayey sequences, where shale gas provides the majority of unconventional occurrences.

Besides the Miocene pelitic sediments accumulated along the axis of the basin, Pannonian basal marls (as Endrőd Marl Formation) and pelitic deposits of Szolnok and Algyő Formations can be considered as potential source rocks (Figure 6.11)

67% of the Miocene source rocks of the basin were evaluated as “good” to “very good”, 66% of the marls of Endrőd Formation ranges “good” to “very good” categories. On the base of chloroform-soluble bitumen content (S_k), the majority of source rock samples of the BCG zone are evaluated as “sufficient”. The parallel evaluation of both values characterises inhibited hydrocarbon migration, which was interpreted as a direct indication of the presence of the BCG zone.

According to the Doboz–1 well data, oil window (R_0~0.6%) starts at 2,400 metres depth, beginning of wet gas generation is expected at 4,300 metres depth (R_0~1.3%), and the dry gas generation is estimated approximately at 5,200 metres depth.

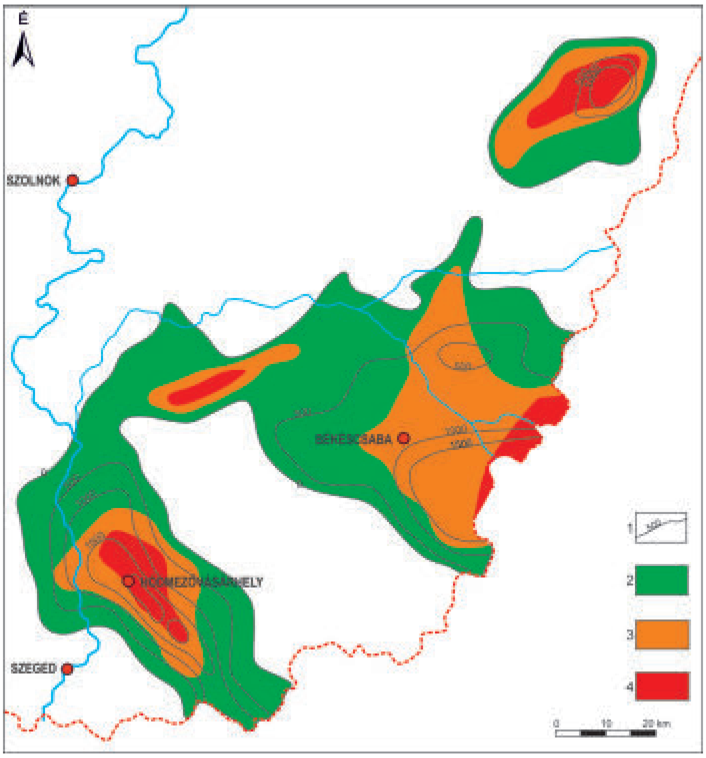


Figure 6.11. Thickness and maturity map of Miocene and Lower Pannonian (Endrőd Marl Formation) in the troughs of the south-eastern part of the Great Hungarian Plain (Alföld) (after Szalay 1988)
1 – thickness (m); 2 – crude oil; 3 – wet gas; 4 – dry gas generation zones

Compaction facies established in the deepest part of the Békés Basin are likely to be characterised by several pressure barriers. These barriers limit the hydrocarbon migration and allow only short migration routes to be formed. Therefore, we can expect hydrocarbon accumulations only within the source rock or within those reservoir rock bodies that are attached to the original source rock.

Pressure barrier be present in Algyő Formation is almost coeval with the oil generation, therefore hydrocarbons trapped in the turbiditic sequence of Szolnok Flysch Formation, or migrated towards the basement, where unconformity boundary directed the migrational pathways to morphologically elevated areas. Pressure barrier, which was formed within the Endrőd Marl, was also played a role in the migration of wet and dry gas in the deep basin. Primary migration is vertical, with upward or downward directions, depending on pressure systems. Migration distances are small; the migration itself is a very slow process. Main migrational pathways are designated by faults. The most likely form of primer migration is to move as a separate phase.

In the BCG zones there are two distinct pressure systems that are evaluated as the main factor for unconventional traps being formed. Mixed compaction facies and massive overpressured facies are forming a basin-sized system, although pressure barriers and conventional traps also may form sub-systems.

Geothermic gradient of the upper section varies between 58–62 °C/km, it is lower at the deepest part of the basin due to the cooling effect of the thick sediment bodies. Geothermic gradient is approximately between 49–51 °C/km along the axis of the Békés Basin, this area has a heat flux of 80–90 mW/m^2. First overpressure value is measured below 2,200 metres, but normal pressure values may present up to 2,500–2,600 metres depth. Overpressure gradient is a bit smaller in the Mesozoic and Palaeozoic basement rocks. Normal and overpressured systems are markedly distinctive within the area, no transition zones were formed.

In Neogene sequences, continuous decrease in porosity can be observed parallel to depth: porosity lesser below 3.0% beneath 4,000 metres depth. In case of silts and marls, porosity decreases quickly to value of 4–5% to the depth of 2,500 metres, below this depth porosity slightly changes with 1% to 4,500 metres depth. Decrease in pore space show different trends in the case of marls thicker than 25 metres than marl layers of 1–5 metres thickness. Normal compaction phase in the case of thick marls terminates between 2,500–3,000 metres depth, so in greater depth thick marl layers have greater porosity of 6–7% approximately, than the thin marl layers. This is the so-called inhibited compaction, which may affect the compaction of deeply buried sandstones as well.

Those sequences, where inhibited compacted clays and sands are alternating with normally compacted strata can be characterised with mixed compaction facies. Overpressured rock bodies are play role as seals, as pressure barriers.

Permeability decreases quickly in Neogene sequences from few hundred mD to 1–2 mD values approximately to 3,000 metres depth, when decrease gets slower and goes beyond 0.1 mD at about 4,500 metres depth. Horizontal permeability has usually greater values than vertical, but around 4,000 metres depth there are only slight differences between the two permeability values. Horizontal and vertical permeability of marls show greater differences in values than of sandstones, there is one order of magnitude difference for the benefit of horizontal permeability to the depth of 2,500 metres. Vertical permeability decreases to 0.1 mD at around 2,000 metres, horizontal is around 3,000 metres depth, but beneath 3,000 metres depth no significant difference are observed between vertical and horizontal permeabilities of the marls. Thickness of marl layers affects the permeability strongly as well: vertical permeability of marl layers thicker than 25 m decreases to 0.1 mD beneath 2,500 metres, when their horizontal permeability decreases below this value beneath 3,500 metres depth. In contrary, marl layers of 1–5 metres thickness become impermeable already around 2,000 metres depth.

The following unconventional accumulations are known from the area:

Szabadkígyós (Gyula I. mining site)

Szabadkígyós–1 well drilled in 2009 the Újkígyós structure, which was ranked previously as high risked exploration object, where series of apparently closing bedheads are leant to a listric fault (SŐREG et al. 2010). However, there is no morphologic closure, gas accumulations are cannot be connected to structural positions, so hydrocarbons can be found in great area around the well in sandstones characterised by poor permeability.

Lower Pannonian Szolnok Formation is the reservoir of unconventional gas accumulation. Bottom of the clayey sandstone is at 3,593 metres depth; its thickness is 690 metres, with an average porosity of 8.8%. Combustible part of the gas is 99.6%, with a calorific value of 38.0 MJ/m^3. the methane content is 95.2%, content of CO_2 is 0%, of N_2 is 0.4%, the C_{5+} content is 0.4 g/m^3 according to the register of the Mining and Geological Survey of Hungary. At 3,233 metres depth, reservoir parameters are the followings: the T_{max} is 158.6 °C and the pws_{max} is 48.165 MPa. Maximum porosity of the turbidite sandstones measured on cores is around 12%. Pore diameter is between 0.2–0.6 µm which is characteristic for tight sandstones. Water saturation is between 45–60%. Well productivity was proven by exploration tests but for commercial production it needs stimulation methods. The 75 km^2 Gyula–I unconventional mining site was assigned between –2,740 – –4,000 m bsl in 2011.

Nyékpuszta (Sarkad I. mining site)

The so-called Nyékpuszta structure, a duplicated Miocene siliciclastic sequence by an overthrust, deposited on the Palaeozoic basement — situated in a narrow trough between Komádi and Sarkadkeresztúr Highs — was drilled by two wells. Gas saturation of the perspective Miocene folded siliciclastic sequence is significant, although its lithophysical parameters are poor. Presence of unconventional reservoir is assumed to present in a thickness of 300–350 metres to approximately 4,000 metres depth. The area of the occurrence is 7.2 m^2. The explored Lower Badenian Nyékpuszta–1 unconventional reservoir (with 290 metres of height) in tight sand became significant secondary porosity during the Badenian. Its exploration well is HHE. Nyékpuszta–1 well drilled in 2009. Combustible part of the gas is 95.5%. Its calorific value is 38.2 MJ/m^3. Its methane content is 81.6%, CO_2 content is 4.3%, N_2 content is 0.2%. Average porosity of the reservoir is 11%, its water saturation is 46%, average permeability is 0.29 mD, reservoir pressure is 77.8 MPa, reservoir temperature is 180.8 °C according to the National Mineral Raw Materials and Geothermal Energy Resources Registry. In the Nyékpuszta–2 well the Miocene sequence starts at depth of 3,610 metres and gas saturated beds was found to 3,900 metres depth.

Gyulavári (Gyula II. mining site)

Two exploration wells were drilled in order to extend further and localise the unconventional hydrocarbon reservoir of the Miocene “Nyékpuszta sequence” known from other areas. As a result, two unconventional free gas accumulations were separated.

The accumulation was explored by Gyulavári–1/B well drilled in 2013. During the drilling, hitting a sandstone–siltstone succession at 4,140 metres depth extremely high gas content was observed. Unconventional reservoirs, called 4,100 m and Turul, are situated within Lower Pannonian thick Endrőd Marl Formation containing sandy interbeds. Areas of the two reservoirs are 95.1 and 208.7 km^2, respectively. Porosity of the clayey sandstone is 9%. The combustible part of the gas averagely is 19.4%, its calorific value is 10.0 MJ/m^3, its methane content is 13.5%, CO_2 0.1%, N_2 80.5%, the C_{5+} content is 35.4 g/m^3 according to the register of the National Mineral Raw Materials and Geothermal Energy Resources Registry of the Mining and Geological Survey of Hungary. Gyula II mining site was assigned on this accumulation between 3,300 and 6,250 m bsl and covers 182 km^2.

HHE-Gyula–1 exploration well drilled in 2009 penetrated in its deep zone the prospective sand sequences of Szolnok Formation and discovered a gas saturated tight reservoir. For the purpose of economic production, there were hydraulic fracturing between 3,550 and 3,565 metres depth. Its base temperature was 168 °C. Production data is visualised on Figure 6.12 concerning the time span and reservoir pressure measured on the wellhead. As an overall conclusion, concerning to the producible amount of gas based on exploration tests of Gyula–1 well the unconventional gas accumulation was considered not commercial even with hydraulic fracturing stimulation.

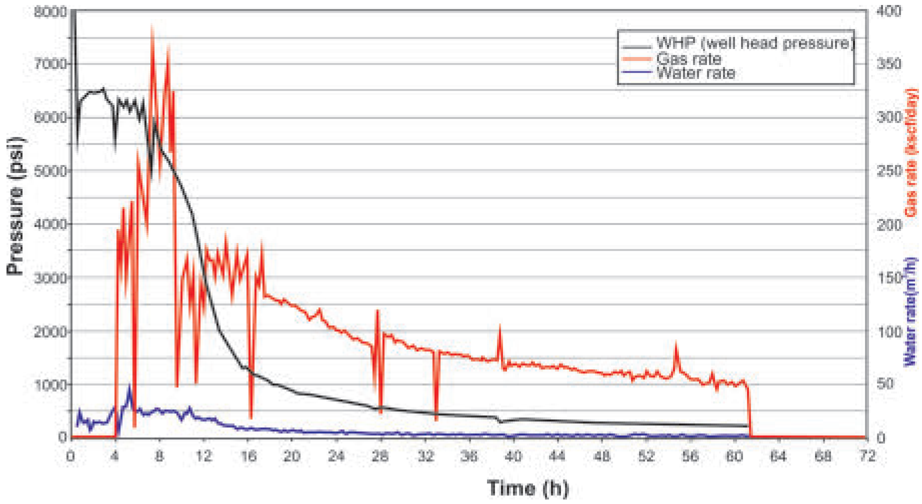


Figure 6.12. Production data of Gyula-1 after hydraulic fracturing (MHE 2010)
Units used in the diagram: 1 psi (pound per square inch) ~ 6,900 Pa; 1scf (standard cubic feet) ~ 0,03 m^3

The Kiskunhalas Trough at the Kiskunság area

RAG Hungary Ltd and its predecessors carried out hydrocarbon explorations in the Danube–Tisza Interfluve (Duna–Tisza köze), at Tompa exploration area (477.38 km^2) of the Kiskunság, between 1999–2009. They drilled seven exploration wells, from which Ba.É–1 penetrated a low porosity and permeability Middle Miocene (Karpatian) sandstone sequence with unconventional hydrocarbon occurrence. This well was turned to a production well after hydraulic fracturing. Other six wells were proven dry, despite previous hydrocarbon explorations recognized several conventional crude oil and natural gas reservoirs in the area.

Unconventional hydrocarbon exploration of the area focuses on Lower Miocene (Karpatian) siliciclastic schlier sequences (Figure 6.13) explored in the Kiskunhalas Trough. The solely production well of unconventional hydrocarbon accumulations of the area is Ba.É–1 well (Balotaszállás–IX mining site, RAG Ltd), although the presence of unconventional hydrocarbons is proven in several other neighbouring areas.

The main conventional reservoir of the Kiskunhalas–III field, owned by Mol Hungarian Oil and Gas Plc, is a Badenian biogenic calcarenite, sandstone and conglomerate, but smaller unconventional reservoirs were also explored in Karpatian tight sandstone bodies. During the exploration drilling process of some wells of Kiskunhalas–VI field, remarkable hydrocarbon indications were observed tied to unconventional type tight reservoirs.

Balotaszállás Ba.É–1 exploration well of Balotaszállás–Deep zone unconventional occurrence was drilled in 2009 and penetrated deposits where formation tests proved the presence of unconventional gas and gas condensate accumulations in the tight sandstone and conglomerate sequences of Middle Miocene Kiskunhalas Formation and in the presumably

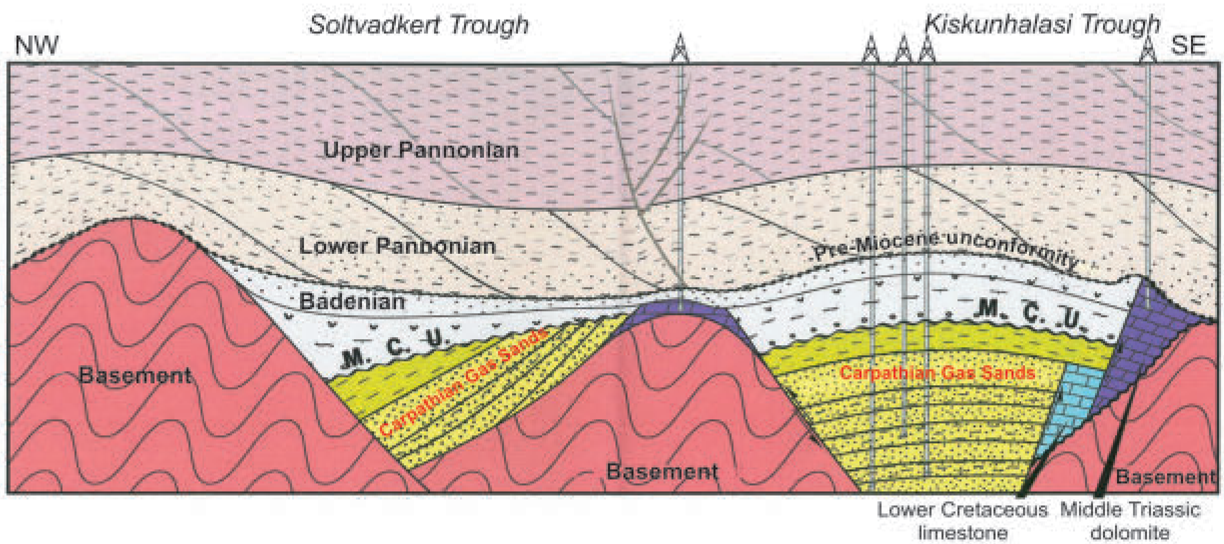


Figure 6.13. Geological section across the Kiskunhalas Trough (M.C.U.= intra-Karpatian unconformity; after GYARMATI 2009)

Ottnangian Szászvár Formation, as well as in argillaceous marl and claystone reservoirs that have also source rock properties. Average porosity related to the total effective rock volume is less than 5%. Permeability values measured on cores and well loggings were less than 0.1 mD in every case. Water saturation data were between 30–70%, but in average was between 35–43% in most cases. Pressure is rarely hydrostatic, rather an overpressure is characteristic which increases parallel to depth and starts from 2,200 metres depth. The produced hydrocarbon is condensate rich natural gas.

Four laterally extended reservoir zones (A–D) were designated in the reservoir succession. *Zone A* is tight sandstone with very low permeability, the base of which is at 3,000 metres depth and the thickness is 250 metres. Combustible part of the gas is 97.8%, its calorific value is 46.1 MJ/m^3. Its methane content is 82.5%, CO_2 1.4%, N_2 0.8%, the C_{5+} content is 149 g/m^3 according to the 2016 register.

Zone B is comprised of heterogenic sandstones of different facies as thick and thin bedded reservoirs, turbidite channel infilling sandstones. Its bottom is at 3,250 metres depth, with a total thickness of 500 metres. Combustible part of the gas is 93.1%, its calorific value is 38.6 MJ/m^3. Its methane content is 80.7%, CO_2 6.7%, N_2 0,2%, the C_{5+} content is 80g/m^3.

Within the *Zone C*, a lower and an upper sub-zone was divided, which can be more accurately divided on the basis of their lithofacies to thin and thick bedded reservoirs. Its bottom is at 4,200 metres depth, with a total thickness of 1,000 metres. Combustible part of the gas is 87.5%, its calorific value is 37.4 MJ/m^3. Its methane content is 74.4%, CO_2 8.1%, N_2 4.4%, the C_{5+} content is 43g/m^3.

It was difficult to define *Zone D* with seismic mapping, so it was just outlined in the surroundings of the wells. Its bottom is at 4,500 metres depth, with a total thickness of 300 metres. Combustible part of the gas is 81.9%, its calorific value is 27.9 MJ/m^3. Its methane content is 81.3%, the CO_2 is 18.1%, N_2 is 0.

Wells drilled in the Kiskunhalas Trough — Kiha–I (2,328 m), Ba.É–1 (1,882 m) — are penetrated in great thickness that Karpatian schlier sequence which is located almost just this area. Strata are elevating towards NE and then are cut by an unconformity or a tectonic feature. Within the sequence, reservoir bodies are the sandstone and conglomerate interbeddings accumulated by submarine gravity flows, while source and seal rocks are the claystones and marls of higher organic matter content accumulated in quieter intervals between gravity flows. Intercalated strata of reservoir and source rocks of Karpatian age provide unconventional hydrocarbon accumulations in tight sandstones characterised by high pressure and high temperature. This accumulation extends to the reservoirs of Ottnangian and Upper Cretaceous tight siliciclastic sequences underlying the Karpatian schlier.

Main reservoir bodies deposited mostly below 2,500 metres depth are composed of thick but laterally limited conglomerate and sandstone layers and beds, as well as source rock bodies of 5–50 metres thick claystones and argillaceous marls which can be characterised by different maturity and can be found in all levels of the sequence. Source rocks mostly generate gas. This sequence was penetrated by Kiha–I and Kiha D–I wells, where continuous gas indications were observed within the Karpatian sequence, although during its formation tests the sequence gave only small amount of non-productive gas content. The sequence has mostly primary, but sometimes secondary porosity as well. Laboratory and CT test (1–7%,) and petrophysical well logging (7–10%) provided slightly different values for porosity, but average porosity reflected to the total effective rock value is less than 5%.

This unconventional hydrocarbon system of Kiskunhalas Trough can be best compared with the tight sandstone system of Derecske Trough, but there is a significant difference between their tectonic position and the hardly correlated stratigraphic position of sandstone lenses related mainly to tectonics. These lenses are more likely tectonic blocks suffered fragmentation during post-transpressional tectonics.

Zala and Dráva Basins

This area is the one first included in hydrocarbon exploration, as well as the first producible industrial oil well can be attached to this area. The area is also a base of further active hydrocarbon research and several different hydrocarbon accumulations and generating systems were found and are under current investigations. Parallel to that, the deep basin areas are also targeted by MHE Ltd to find unconventional hydrocarbon accumulations in two exploration areas.

Lenti exploration area

Between 1999 and 2003 MHE Ltd have been explored the area of Szentgyörgyvölgy–Csesztreg which is in the Őrség part of the Zala Basin to find natural gas accumulations. Main goal of the project would have been to test and convert into production the Middle Miocene, Badenian shallow marine light oil/condensate and gas containing sandstone known from Szen–1 well. Kógyár–1 hydrocarbon exploration well was drilled in 2001 by MHE Ltd to the total depth of 3,240 metres. There was a biogenic limestone and calcareous marl (Lajta Limestone Formation) deposited in the top zone of the Badenian reservoir, while below it a shallow water fine-grained sandstone, turbidite and siltstone (?Tekeres Schlier Formation) have been found. Laboratory testing and measuring of cores proved the presence of variable, but overall unfavourable porosity and permeability values of a hydrocarbon reservoir which although contains combustible gas and light oil of excellent quality.

Main hydrocarbon system of the area is within Middle Miocene sequences, mostly of Badenian age. Producible amount of hydrocarbon accumulation was proved by Szen–1 well, which produced pure natural gas, oily condensate and water from shallow marine littoral facies sandstones from 3,193 metres depth.

Source rock is a Badenian argillaceous marl and marl, which contain pyrite in greater depths. The overpressured sequence suggests great amount of hydrocarbons were able to generate in the system. Reservoir rocks are carbonated microconglomerates with matrix porosity, as well as fine grained sandstones, but some frustration cannot be excluded. Because source rocks and reservoirs are mostly attached to each other or source rocks represent the pelitic facies of the reservoirs, primary and lateral migration are the most likely migration. Bottom of the accumulation is marked by the top of the Badenian transgressive marl, while its top is marked by the littoral level. Hydrocarbon trap is a structural trap sealed by tectonic elements.

The reservoir sequence was explored in a littoral facies by the Szen–1 well, while Szen–2 and Szen–I wells penetrated it in pelitic facies and at Szen–5 well the reservoir was saturated with water. On the basis of 14 measurements, porosity was between 2.65–7.89%, while permeability shows 10–2 mD scale. Permeability values greater than ~1 mD were measured on the Badenian turbidites characterised by porosity values higher than 10% in siliciclastic sequences.

At Kógyár–1 well the reservoir sandstone facies can be divided into three megacycles, which can be identified in Szen–4, Szen–5 and Szen–I wells as well. According to the data obtained until now, the upper megacycle is the hydrocarbon reservoir, older ones are far too tight or/and contain water. At Kógyár–1 well between 3,164–3,173 metres the upper reservoir megacycle was core-drilled, and the characteristic turbidite structure was observed. Porosity maximum of 11% was measured between 3,159–3,161 metres, 10% was measured between 3,162–3,163 metres, at both levels clay content also shows a relatively low value of 12%. Water saturation was between 40–70%. Production tests were carried out between 3,143.0–3,176.5 metres MD, where the well was produced discontinuously 100 m^3/day gas and 0.03 m^3/ light oil/condensate per a day. Oil is naphthenic with 824.7 kg/m^3 density. According to the pressure curve the effective permeability for oil and gas k_g is 2.42×10^{-4} mD and k_o is 1.19×10^{-4} mD. Reservoir rock is practically tight sandstone. Producible amount of hydrocarbons can be expected in the fractured zone or from its immediate vicinity. Petrophysical parameters of the reservoir and formation tests suggest that supply area of the production wells can be estimated as too small, and without hydraulic fracturing the continuously producible amount of hydrocarbons does not hit the economic level, so stimulation processes are needed.

Letenye exploration area

The exploration area covers 221 km^2 and there are 10 exploration wells drilled here related to the previous, intensive hydrocarbon exploration processes. These wells are mostly located on the edges of conventional hydrocarbon accumulation covered yet by mining sites. Main geologic structure of the whole area is the system of Sava folds of SW–NE strike. Upper Pannonian sequence was also affected by folding, which sometimes outcrop at the centre of anticline structures.

Budafa Anticline is situated at the northern margin of the research block; its southern limb is a part of the Letenye exploration area. Pannonian hydrocarbon-bearing deposits can be reached by shallow drilling so more than 500 wells were drilled in the area. Initial wells reaching greater depths were drilled between 1940–1959, but Badenian–Karpatian formations appeared to be very tight and produced decreasing amount of natural gas. Along with the development of geophysical methods, more and more deep wells were drilled penetrating thick Middle Miocene, mostly Sarmatian, Badenian and Karpatian deposits and reached the Mesozoic carbonate basement. In Letenye exploration area no hydrocarbon accumulation was found until now, only indications were observed in overpressured Middle Miocene and pre-Cenozoic basement deposits.

B–II and B–IX wells drilled at the southern limb of the Budafa Anticline structure, initially produced significant amount of dry gas (daily 190–263 thousands m^3, and 3500 m^3) from the Karpatian and Triassic carbonate breccias and shales from 4,000–5,000 metres depth, but this was followed by a rapid decline in well production rate and well-head pressure. West from the Bajcs basement ridge at Semjén area, Sem–1 well have not reached the basement, though several weak oil and gas shows were observed. Sem–2 well reached the Permian/Triassic basement and 490 m^3 gas inflow was measured. Sem–3 well was installed to a local height, and provided 2,490 m^3 gas daily through a 4 mm pipe from Triassic basement rocks.

There were four wells drilled around Letenye to explore a ridge deepening towards east where strong gas and oil indications were measured. Between 3,750–3,755 metres of Le–I well, daily 15,700 m^3 gas and 640 m^3 water was produced through a 10 mm pipe but along with decreasing pressure values. On the basis of several 100 m^3 water production, permeability can be favourable.

According to formation tests, gas indications can be referred to wet gas at Le–I, –2, Sem–2, –3 wells, where wet gas have more likely the same common origin with accumulations of the surrounding areas. Dry gas indications of deeper levels are originated from a different source rock of a different hydrocarbon system. Karpatian black schlier deposits of the deepest areas of former troughs are turned into the dry gas zone and on the basis of their Type III organic matter content, they mainly generate natural gas. Time closeness of dry gas generation and uplifting of the source rocks suggests the generation of free gas phase and unconventional accumulation of the gas in Karpatian formations characterised by poor permeability.

Neogene pelitic rocks are appropriate source rocks mostly. In Zala Basin, Zagyva Formation can be characterised by high organic carbon (C_{org}) content, but its immature source rocks are not involved in thermal hydrocarbon generation processes. Average organic carbon content was only exceeded by the C_{org} content of Sarmatian pelites. Organic content of Karpatian formations shows great dispersion, but on the basis of point data it rarely exceeds 0.8%. Organic content of Sarmatian and Badenian sequences is Type II and III, Karpatians is III, mostly huminic. All of these three Middle Miocene units can be considered as potential source rocks, due to the great thickness of the pelitic sequence that can reach several hundred metres at certain points.

In Letenye block, maturity of organic matter can reach the vitrinite reflectance value R_0 1,3% below 3,400 metres depth, which is to the limit for wet gas generation in this area. According to vitrinit reflectance data, Lower Pannonian delta front sediments (Szolnok Fm) and basal marls (Endrőd Marl) are in the oil window at the tectonically inverted part of the block. Main zone of crude oil generation and the zone of wet gas generation were reached by Sarmatian and Badenian shallow marine deposits. Karpatian sequences are currently in the dry gas generation zone. On the basis of thermal datasets from well tests and geophysical well logging methods, thermal gradient is 48 °C/km until 3,000 metres depth, and slightly decreasing below this depth. Overpressure starts around 3,000 metres depth, but occasionally can be hydrostatic in the basement formations below the overpressured zone. Overpressure characterises thick Miocene marls mostly. Normal compaction process of the marls ends around approximately 2,000 metres depth, porosity of deeply buried sequences has not change significantly according to the inhibited compaction. The primary porosity is around 5%. Siltstones and sandstones can be characterised by gradual porosity decrease, pore obstruction and inhibited compaction is very unlikely. At BCG zone siltstones has 6–8% average porosity, while sandstones 7–10%. Porosity of fractured carbonate reservoirs neither exceeds 3–4%.

Beneath 2,000 metres depth, pelites can be characterised with significant similarity in horizontal and vertical permeability which marks the end of compaction. In cases of sandstones, anisotropy in permeability remains in all depth, in BCG zone characteristic values are between 0.1–1.0 mD. In the inversion zone, permeability may grow with fracturing originated from intense tectonic movements and steep dipping strata (30–70°). These parameters and phenomena characterise mostly Middle Miocene Karpatian and Triassic basement rocks.

Shale oil and shale gas potential of Kössen Marl

Upper Triassic Kössen Marl Formation situated in the Palaeo–Mesozoic basement of the Zala Basin, due to its significant extension area, favourable organic matter content and maturity, can be considered as a huge potential for unconventional shale oil and shale gas accumulation (Badics, Vető 2012, Anthonsen et al. 2016) (Figure 6.14).

Kertai (1968) was the first who discovered that possibly Upper Rhaetian – Norian organic rich marl can be the source rock of Nagylengyel oil accumulation discovered in the northern part of the Zala Basin. Later Koncz (1990) and Clayton, Koncz (1994b) proved the connection between the oil accumulation and source rock with geochemical analysis, so the presence of "Kössen–Cretaceous"(!) hydrocarbon system in the sense of Magoon, Dow (1994) can be proved and known (Badics, Vető 2012). Kössen Marl Formation is known from wells to be present deeply buried in the pre-Cenozoic basement and also outcropped on the surface in the Transdanubian Mountains. 230 wells reached Triassic basement rocks, but only 32 of them penetrated the Kössen Marl. In many places the formation was eroded during the Alpine orogenic phase

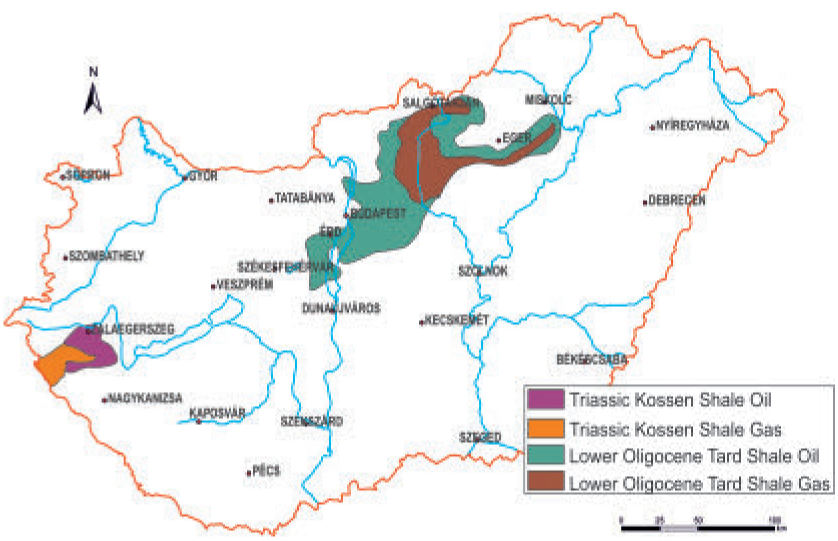


Figure. 6.14. Shale gas and shale oil formations of Hungary (after Badics, Vető 2012)

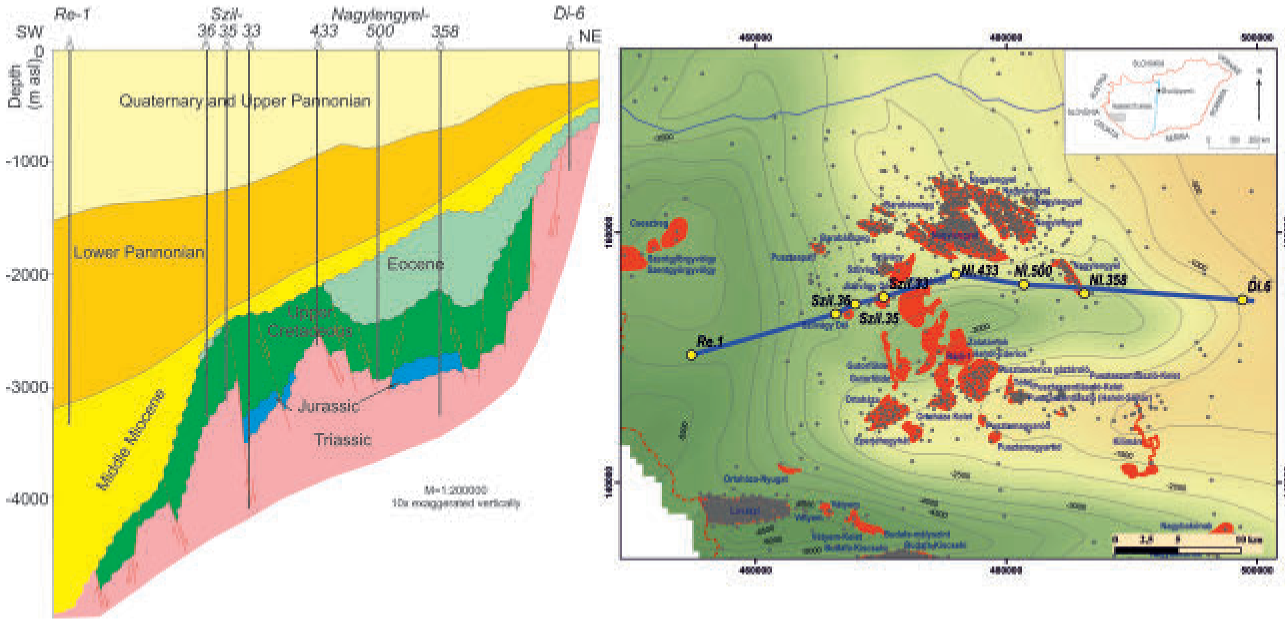


Figure 6.15. Geological sketch map along the hydrocarbon accumulations of the Szilvágy and Nagylengyel (on the left) in the Zala Basin and map of the area showing the most important wells (after Clayton, Koncz 1994b)

Discovered accumulation areas are shaded. NL: Nagylengyel, SZIL: Szilvágy. Contour lines show the depth below see level of the basement of the pre-Cenozoic basement

in the Cretaceous–Palaeogene time interval (Kőrössy 1988). Thickness of Kössen Marl varies between 17 and 575 metres, 200 metres in average in the Zala Basin. Its extensional area is 1,500 km^2 (Badics, Vető 2012). Top surface of the Triassic rocks deepening towards west, their extension to Slovenia cannot be assured (Figure 6.15).

Organic geochemical features of the Kössen Formation are documented in details (Bruckner-Wein, Vető 1986, Hetényi 1989, Vető et al. 2000, Hetényi et al. 2002) mainly on the basis of Zalaszentlászló Zl–1 and Rezi Rz–1 wells. In both wells kerogene is immature and of type II. Value of vitrinite reflectance is 0.32–0.35%, T_{max} value is between 395–435 °C. On the basis of 131 samples, TOC (total organic carbon) content is between 0.07–31.5%, averagely 3.86%, average S_2 is 22 mg CH/g rock, HI hydrogen index on average is 516 mg CH/g TOC. Total carbonate content varies between 40–90%, quartz is between 4–20%, clay mineral content is between 8–42%. Clay minerals mostly composed of kaolinite and illite/smektite (Vető et al. 2000, Hetényi et al. 2002, Badics, Vető 2012, Schovsbo et al. 2017). There are no public Rock-eval data from matured source rock bodies.

History of basin subsidence is outlined by Clayton, Koncz (1994b) (Figure 4.2.8) in the area of Nagylengyel. Thermal and maturity evolution, the process of hydrocarbon generation in the Zala Basin have been investigated recently by Badics, Vető (2012). According to their 3D modelling, burial and thermal maturity took place mainly in the Neogene, in accordance with the results of Clayton, Koncz (1994b). Deepest parts of the Kössen Marl Formation present temperature is 250 °C. In the south-western part of the basin, the succession with an extent of 270 km^2 is in the gas generation zone, beneath the Nagylengyel oil field with an extent of 450 km^2 is in the oil generation zone. In its north-eastern part of 780 km^2 it is immature. Presuming that 40% of matured hydrocarbons stayed in their source rock, the amount of non-migrated hydrocarbons (initially in place) can reach an equivalent value of 1.4 billion m^3 (9 Bboe) crude oil. A certain percentage of this amount may remain in the oil generation zone as crude oil, while in the western, deeply buried part of the basin went through decomposition and accumulated as potential shale gas (Badics, Vető 2012).

According to the estimates of the European Union working group on unconventional oil and gas accumulations (EUOGA) (Anthonsen et al. 2016, Schovsbo et al. 2017, Zijp et al. 2017), the probabilistic P50 estimate of the in-place shale oil generated by the Kössen Marl is 4 million m^3, the free gas estimate is 77 billion m^3, the adsorbed gas estimate is 24 billion m^3.

According to the USGS estimates based on geological and geophysical datasets (Schenk et al. 2017), the risked prospective, undiscovered, technically recoverable estimate of the Kössen Marl shale oil with P50 probability is 4,1 million m^3 (26 MMBO)(mean is: 4,8 million m^3, 30 MMBO). Chance of success, or the geological probability was estimated for both oil and gas is 0.9 (90%). For the matured oil zone, which is the so-called "oil window", the P50 probability estimate value of the prospective recoverable natural gas is 1.4 billion m^3 (51 BCFG)(the mean is 1.7 billion m^3, 59BCFG), with 0.15 million m^3 (1 MMBNGL) gas condensate. In the matured gas (gas window) zone the recoverable amount of P50 quantity is 1.5 billion m^3 (54 BCFG), (mean: 1.7 billion m^3, 59 BCFG), with 0.15 million m^3 (1 MMBNGL) gas condensate.

Nyírség–Tiszavasvári unconventional hydrocarbon accumulation

Certain deep basin areas of Nyírség are proven to be a target of future exploration and production of unconventional hydrocarbons according to the most recent integrated exploration. In the geological setting of the Nyírség sub-basin and its wider surroundings the several thousand metres thick Neogene and Quaternary sediments play the dominant role. Neogene sedimentary rocks were deposited in small, but rather deep (3,000–4,000 m) sub-basins which are divided from each other by uplifted heights (BODOKY et al. 1977). According to SZEIDOVITZ et al. 2003, these sub-basins are tectonically still active. The main structural element of the area is a supposed megastructural boundary line with NNE–SSW strike, but its exact position and the lithology and structure of the basement are still less known.

The HHEN–Tiv–6 well was drilled in 2010 and discovered a Miocene unconventional tight gas accumulation in sandstone, to which the Tiszavasvári–IV mining site was established. In its broader surroundings two hydrocarbon system were identified: north of the Balaton Line (centred in the Vatta–Maklár Trough) a Palaeogene, mostly oil generating system is situated, while south of the Nyírség a Neogene hydrocarbon system was recognised centred in the Jászság Basin. The Tiszavasvári accumulation belongs to the latter one.

Primary source rocks of the Tiszapalkonya Basin are Pannonian deep marine marls with an average organic content of 1% measured in exploration well cores. Nevertheless, some parts of Algyő Formation have surprisingly high, although immature organic content of 2.0–2.5% TOC, which has presumably terrestrial origin on the base of the hydrogen index (mg HC/g TOC).

Below 2,600 metres depth of the Miocene sequence of HHEN–Tiv–6 well, there are interbeddings of source rocks with exceptionally high organic content of 4–6% TOC, which on the basis of their 100 mg/g HI values can be tied to mostly gas generating terrestrial origin. In general it is concluded that organic content of Miocene sequences from all the examined wells can be characterised by a mixed Type II–III kerogens.

According to the geochemical analysis of rock cuttings from HHEN–Tit–1 and HHEN–Tiv–6 wells, Tiszapalkonya sub-basin has an extremely high geothermic gradient of 65 °C/1,000 m, this means the beginning of the oil window marked by a value of 0.6% vitrinite reflectance can be placed around 2,000 metres depth (TÓTH, WÓRUM 2015).

The same oil window boundary can be placed around 2,500 metres depth in other areas of Hungary. According to the observations described above, it can be concluded that deep basin areas of Jászság, as well as Tiszapalkonya Basin are in the phase of hydrocarbon generation now. Hydrocarbons generated in these areas were migrated along the pre-Pannonian unconformity and the Lower Pannonian sand beds towards the margins of the basin where were trapped mainly in structural traps (Hajdúnánás, Tiszavasvári, Tiszagyenda).

In the productive HHEN–Tiv–6 well almost continuous gas indication was observed from 2,480 metres depth in the drilled Lower Pannonian and pre-Pannonian sequences. This sequence is thicker than 300 metres and contains several sandstone beds which porosity is between 10–15%, but a detailed analysis showed their permeability is less than 0.1 mD and strongly depends also on formation pressure. Five sections were perforated which gave good quality of combustible gas from low permeability tight sandstones. After perforation of sandstone beds between 2,777.5–2,780.0 metres depth, at closed wellhead the pressure elevated to 265 bar. Unfortunately, after opening up the wellhead, the pressure decreased very slowly and only gave gas indication with 0.8 bar. After perforation of other sandstone beds, a daily ~6,800 m^3 gas was reached with 32 bar of wellhead pressure. For continuous economic production from these hydrocarbon accumulations in Miocene sequences, further hydraulic stimulation processes needed. Calorific value of the accumulated gas is 36.8 MJ/m^3. Its methane content is 84%, CO_2 content is 4.8%, N_2 content is 0.1%.

Shale gas and shale oil potential of the Hungarian Palaeogene Basin

There were no targeted exploration focused on unconventional oil accumulations of the basin, but our present geological–geophysical knowledge, together with the presence of thick, matured source rocks, the inversion of the basin (which means in certain areas source rocks were buried more deeply and later got into an uplifted position) and presence of conventional hydrocarbon accumulations rewarding the area as a potential target of shale oil explorations.

Characteristics of the hydrocarbon systems of the Hungarian Palaeogene Basin, together with its overall geological background was outlined at the description of conventional accumulations, so here we focus only to the data and information related to the exploration of shale oil and shale gas.

Main source rocks are the Lower Oligocene Tard Clay Formation and the overlying Kiscell Clay Formation with far lower source rock potential (KÓKAI, POGÁCSÁS 1991, MILOTA et al.1995). Generation of hydrocarbons began in the Miocene and still continues nowadays, depending on tectonic movements of the source rocks and their basin subsidence and burial history.

In the Palaeogene basin there were 443 wells reached the Tard Clay Formation, from which only 85 penetrated it in its whole thickness (KŐRÖSSY 2004). Its thickness is between 8–200 metres, averagely 68 m, its total extension is 7,800 km^2.

Detailed oil-source rock correlation was not carried out, therefore the Tard–Kiscell hydrocarbon system in a meaning by MAGOON, DOW (1994) is rather hypothetic.

Geochemical and sedimentological characteristics of the Tard Clay formation were described by BRUCKNER-WEIN et al. (1990), VETŐ, HETÉNYI (1991), VETŐ et al. (1999) on the basis of detailed analysis of Alcsútdoboz Ad–3, Cserépváralja Cs–1, Nagykökényes Nk–I and Veresegyháza V–1 wells. The uppermost part and the lower half of the formation is non-laminated marly sequence, in contrast with the rest of the laminated silty upper part. This latter lithology sometimes can reach 60% clay mineral content, which is more reduced to 30–40% in the marly strata. Smektite content can reach 30–40% among the clay mineral fraction (VICZIÁN pers. comm.).

According to the 3D regional basin model of BADICS, VETŐ (2012), the sequence is immature above 1,300 metres depth, between 1,300–3,000 metres it is in the oil generation zone (0.6–1.3% R_0), beneath 3,000 metres depth in the gas generation zone, but Lower and Middle Miocene volcanism may have caused some variability. In the middle of the basin, north from Nk–1 well, the deepest part of Tard Clay can be characterised by a temperature of 220–250 °C, in the gas generation zone. In the north-eastern part of the basin, between Demjén and Mezőkeresztes oil fields the sequence is also in the gas generation zone. The overall extension of the oil generation zone is 1,900 km^2, the gas generation area is approximately 2,600 km^2 and the immature area is 3,300 km^2. Based on this model, the value of the non-migrated hydrocarbon potential may reach 7 billion barrels (1,1 billion m^3). Main parameters used in this calculation are the following: average source rock thickness: 27 metres, original total organic carbon content (TOC): 2.21%, hydrogen index (HI): 433 mg CH/g TOC (BADICS, VETŐ 2012).

According to the estimates of the European Union working group on unconventional oil and gas accumulations (EUOGA) (ANTHONSEN et al. 2016, SCHOVSBO et al. 2017, ZIJP et al. 2017), the probabilistic P50 estimate of the shale oil generated from the Tard Clay is 199 million m^3, the free gas estimate is 482 billion m^3, the adsorbed gas estimate is 230 billion m^3.

According to the USGS estimates based on geologic and geophysic datasets (SCHENK et al. 2017), the risked prospective, undiscovered, technically recoverable estimate of the Tard Clay shale oil with P50 probability is 12.6 million m^3 (79 MMBO) (mean is: 14.1 million m^3, 89 MMBO). Chance of success, or the geological probability was estimated for both oil and gas is 0.8 (80%). For the matured oil zone (oil window), the estimate with P50 probability for the technically recoverable natural gas is 4.3 billion m^3 (152 BCFG) (mean: 5.0 billion m^3, 178 BCFG), with 0.5 million m^3 (3 MMBNGL) gas condensate (the mean is 0.6 million m^3, 4 MMBNGL). In the matured gas zone the technically recoverable natural gas value of P50 is 2.2 billion m^3, 79 BCFG), (mean: 3.2 billion m^3, 114 BCFG), with 0.3 million m^3 (2 MMBNGL) gas condensate.

Hydrocarbon resources of Hungary

Zsolt Kovács

Structure of the Registry system of the Hungarian hydrocarbon resources

Hungarian hydrocarbon resources are registered by the Mining and Geological Survey of Hungary (MBFSZ), in accordance with the operative, but several times modified Mining Act (Act XLVIII. of 1993 on mining). Data supply to the Hungarian State Mineral Raw Material and Geothermic Energy Resources Registry is based on the obligatory yearly data supply of mining contractors; MBFSZ produces yearly datasets from them.

The information contained in the hydrocarbon register contains information on units referred to hydrocarbon reservoir levels field by field. In hydrocarbon industry reservoir levels equal to certain accumulations, which can be delimited from their surroundings and can be characterised as a certain, coherent unit containing natural hydrocarbons. Hydrocarbon field means a certain area of several reservoirs connected to each other by hydrocarbon geologic or production point of view and can be outlined as a certain geometric structure. All data included in Registry are relevant to 1st of January of each year and contains changes were undergone during the previous year and were given by each mining companies. This registry can contain data related to already discovered, explored hydrocarbon accumulations, prospective resources which are not proven to be present with exploration wellbores or geologic/geophysical well loggings, are strictly not allowed to be included. It contains names and identification codes of all fields and reservoirs, as well as information on field development status, the cause of changes on the current state of each field. The register database contains data of hydrocarbon quantities for each and every reservoir as follows: resource initially in place, initially recoverable resource, summarised production and loss, production and loss of the actual year, and the recoverable resource as of January 1. These data and information sets are separately given for conventional crude oil, free natural gas, gas cap gas, dissolved gas, CO_2 gas and for unconventional gas and condensate resource quantities. Resource of a reservoir is given as a certain number for crude oil per thousand tons, for natural gas per million m^3 units.

Besides resources data, the registry contains basic parameters for crude oil and natural gas, such as their composition, along with fundamental parameters of the reservoir such as the depth of oil-water, gas-water, gas-oil contact boundary compared to relative sea level, porosity, permeability, gas- and oil saturation, besides other information required for mineral resource estimation. Also provides data about the applied recovery techniques and methods, quality of the reservoir rock, water supply of the reservoir, number of drilled exploration and production wellbores. Registered parameters of the reservoir are the quality of the reservoir rock, mineral composition and physical parameters of its reserved fluid content, which are all initial and required information for resource estimations.

In contrast, the registry does not include data since 2010 on commercial recoverable reserves, cost limit of the commercial value of the explored reserve, real costs, so evaluation of commerciality is committed to the contractor (Kovács 2016).

Quantity and quality of the Hungarian registered hydrocarbon reserves

Certain sub-areas related to the Hungarian hydrocarbon exploration and production are shown on Figure 3.4 and Table 3.1.

According to the 1st of January 2016 state of the registry, there are 1,429 reservoirs of 304 conventional hydrocarbon fields, and 25 reservoir levels of 9 unconventional fields are listed. Summarised crude oil and natural gas resources data for conventional hydrocarbon accumulations are shown on Figure 7.1.

Total amount of recoverable conventional hydrocarbon resources of Hungary is 21.3 million tons of crude oil and 80.1 billion m^3 natural gas, according to available registry summaries. It is also worth mentioning that of this 80 billion cubic meters of natural gas, 40% is low quality natural gas with low heating value and with unfavorable composition consisting of a high amount of inert, incombustible gases. These low quality gases may characterised with 15–90% carbon dioxide content, the so-called CO_2 natural gas has more than 90% CO_2 content. Besides the inert CO_2, nitrogen content can be high as well, sometimes high up above 20% in certain reservoirs. Value of natural gas with extremely high inert gas content (50–90%) is approximately 17 billion m^3. These natural gases contain very low amount of any combustible component, mostly production fails due to this high CO_2 content.

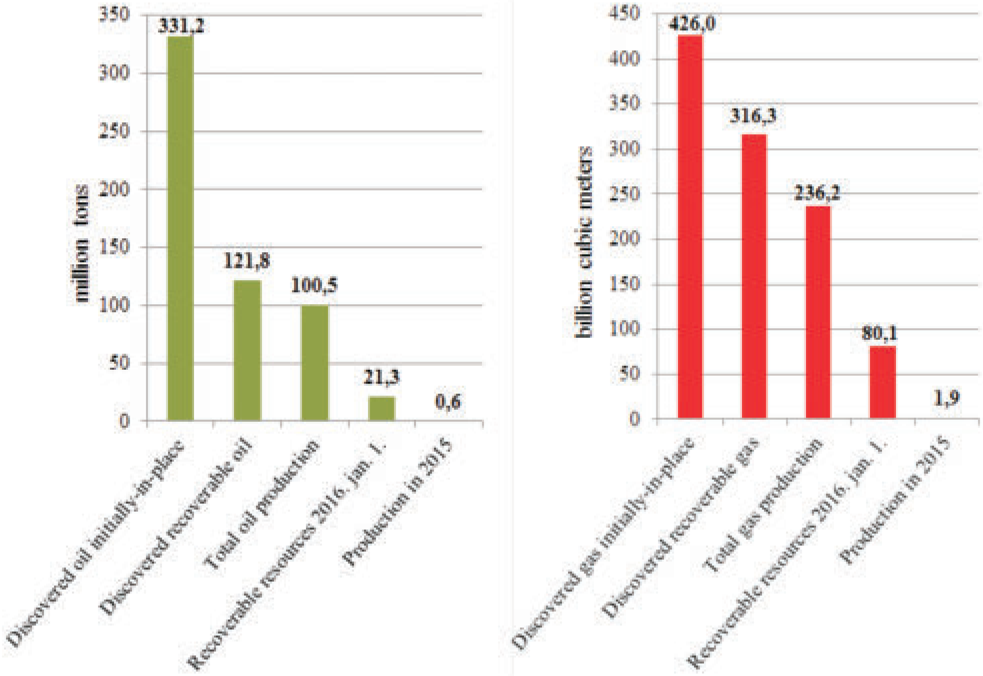


Figure. 7.1. Summarised hydrocarbon resources registered by the Mining and Geologic Survey of Hungary (MBFSZ), as of January1, 2016 status (Million ton values of crude oil are coloured green, billion m^3 values of combustible natural gas are coloured red.)

Recoverable amount of natural gas resources with high (30–50%) inert content is remarkable, approximately 13 billion m^3. In average, half of this amount is the practically combustible gas part. Using proper inert gas separation techniques and appropriate, environmental friendly handling of the separated CO_2, these accumulations may turn into production.

The quantity of in-place and recoverable resources given by actual status may vary due to the decline because of production, the growth because of discovery of new accumulations and the possible revaluation. Revaluation is based on re-interpretation of previous datasets, or changing the production technology which may correct previous evaluations to more precisely. Recoverable resources of conventional hydrocarbon accumulations show decreasing trend considering a long-term period (Figure 7.2), because new exploration results cannot balance positively the continuous productions and revaluations.

A decrease in resources may be related to the decrease in hydrocarbon exploration activity. Since 1990, exploration techniques went through remarkable changes. Number of wildcats declined along with the intensive improvement of exploration equipment and methods as 3D seismic acquisitions and processing, well logging methods, information technologic methods, software etc. Thanked to these more effective new techniques which provide higher quality interpretation, producible amount of hydrocarbon resources had not declined more spectacularly.

Recoverability does not necessarily mean that the planned field development of the discovered in-place hydrocarbon

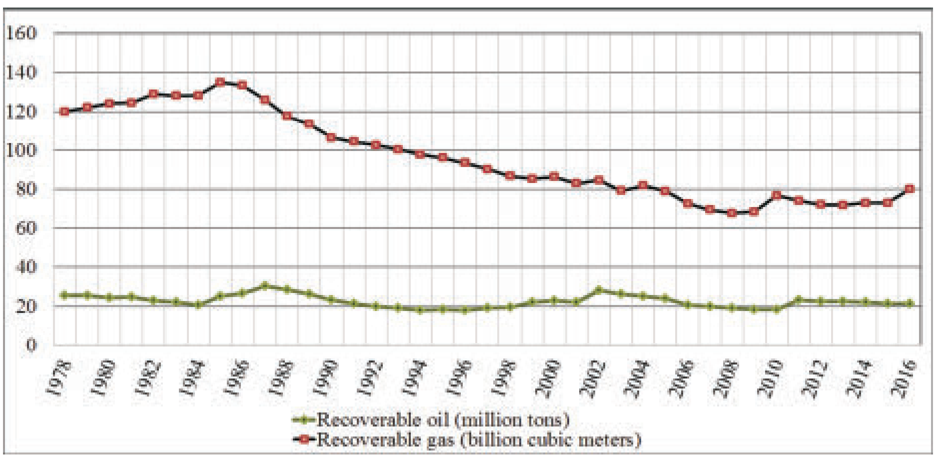


Figure 7.2. Changes in recoverable quantity of discovered hydrocarbon resources

resource would be commercially valuable or even possible. Sometimes other, non-geologic reasons, e.g. lack of certain permissions, more likely a presence of environmental protection or inhabited area, or lack of infrastructure may obstruct to turn a hydrocarbon field into economic production. Besides, geologic reasons as small field area or low quality hydrocarbon content may result the same. Evaluation of a certain field by economic point of view is handled as a business secret and depends on the decision of the mining company.

Declining quantity of conventional hydrocarbon resources can be complemented with exploration of unconventional accumulations. According to the registry of MBFSZ, currently there are 9 concession mining plot areas has permission to explore and turn into production unconventional hydrocarbon occurrences. Based on production tests, presence and commercial value of gas from low permeability tight sandstones is proven. According to the registry data given by certain mining companies interested in unconventional hydrocarbon production, their summarised value may reach 3,900 billion m^3 in-places, from which 1,500 billion m^3 may be the theoretically recoverable value. These are enormous amounts compared to the yearly 2 billion m^3 conventional hydrocarbon resources, but the truly produced amount was only 40 million m^3, and needs more exploration and evaluation until turn unconventional fields into commercially valuable production (KOVÁCS ZS, FANCSIK 2015).

Hungarian hydrocarbon fields and their resources

Based on the registry of hydrocarbon mineral resources of the Mining and Geological Survey of Hungary, the crude oil, combustible natural gas, CO_2 gas, unconventional combustible gas and unconventional gas condensate resources were summarised by hydrocarbon fields. This register contains the identity number of the sub-basin, the name of the field, the type of raw material (oil, gas, condensate) known from the field, the number of reservoirs in the field, the initially in-place quantity of the field, the estimated recovery in percentage, and the already produced amount.

The initially in-place quantity of hydrocarbon resources can be estimated with more accuracy during the production in progress, so the resources are re-evaluated time-to-time by the company, and this re-evaluated amount will be the re-evaluated initially in-place resource hereinafter. Initial in-place resource multiplied with the estimated recovery means the initially recoverable amount of the resource. The difference between the initially recoverable resource and the total production calculated for the current year gives the amount of the actual recoverable resource.

In the following tables, numbering of the sub-basins are corresponds to the numbers given in Chapters 3 and 4 for each area.

1. Danube Basin, Little Hungarian Plain,
2. Zala and Dráva Basin in the Transdanubian part of Hungary,
3. Szeged Basin and Kiskunság in southern part of the Great Hungarian Plain,
4. Battonya–Pusztaföldvár High and Békés Basin in the southern part of the Great Plain,
5. Nagykunság, northern part in the Great Plain,
6. Nagykunság, south-eastern part in the Great Plain,
7. Bihar, in the south-eastern part of the Great Plain
8. Nyírség, in north-eastern part of the Great Plain
9. North Hungarian Palaeogene Basin.

Crude oil occurrences

In Table 7.1, summarised resources data of 344 crude oilfields are listed, on the basis of Registry of Mineral Resources in 1st January, 2016.

There are no known accumulations in the (1) Danube Basin area. In other hydrocarbon sub-basins there are 143 hydrocarbon fields which contain at least one crude oil reservoir. A reservoir may be undersaturated oil accumulation (only with dissolved gas content, or even without it), or saturated oil reservoir (besides the dissolved gas content of the oil, gas cap is present). Dissolved and cap gas can be combustible natural gas, or CO_2 natural gas, which means at least 90% of the accumulated gas is CO_2.

Table 7.1. Parameters of Hungarian crude oil fields (O: oil, G:gas, C: CO_2)

No	Sub-basin	Oil field	Oil/Gas/CO_2 reservoirs in the field	Number of reservoirs	Number of oil reservoirs in the field	Discovered oil initially in place (kilotons)	Estimated recovery (%)	Total oil production (kilotons)
1	2	Barcs	OG	4	1	45.1	5.3	2.4
2	2	Belezna	OG	2	2	399.9	21.5	41.5
3	2	Belezna-Dél	OG	3	1	41.6	12.5	0.0
4	2	Belezna-Kelet-1	OG	2	2	957.9	16.7	0.0

Table 7.1. Continues

No	Sub-basin	Oil field	Oil/Gas/CO_2 reservoirs in the field	Number of reservoirs	Number of oil reservoirs in the field	Discovered oil initially in place (kilotons)	Estimated recovery (%)	Total oil production (kilotons)
5	2	Budafa-Kiscsehi	OG	7	7	16728.0	34.9	5664.7
6	2	Buzsák-I.	O	1	1	119.0	30.0	35.4
7	2	Darány	OG	3	2	55.3	20.1	0.0
8	2	Darány-Nyugat	O	2	2	5475.3	3.0	0.0
9	2	Eperjehegyhát	O	1	1	175.4	8.7	0.0
10	2	Görgeteg-Babócsa	OG	15	2	42.8	20.1	2.0
11	2	Hahót-Ederics	O	1	1	16.5	37.6	6.2
12	2	Heresznye	OG	10	4	38.4	14.3	5.4
13	2	Homokszentgyörgy	OG	3	2	424.5	29.8	0.0
14	2	Jankapuszta	O	1	1	556.6	2.4	0.0
15	2	Jánosmajor	OG	2	2	433.9	21.0	29.7
16	2	Kadarkút	O	1	1	766.4	25.0	0.0
17	2	Lovászi	OG	7	5	21312.0	31.0	6584.6
18	2	Mezőcsokonya-Nyugat	OG	1	1	866.8	16.4	91.2
19	2	Nagyatád	O	1	1	7668.0	15.0	0.0
20	2	Nagybakónak	OG	2	2	164.8	12.3	0.0
21	2	Nagylengyel	O	14	14	39823.0	53.6	20602.9
22	2	Nagylengyel-Barabásszeg	O	1	1	2930.0	40.8	1074.5
23	2	Nagylengyel-Szilvágy	O	1	1	390.0	76.6	248.8
24	2	Nagylengyel-Szilvágy-Dél	OG	1	1	252.5	13.3	31.1
25	2	Ortaháza	OG	19	10	2691.1	30.7	649.1
26	2	Ortaháza Kelet	OG	5	1	208.4	30.4	63.4
27	2	Ortaháza-Nyugat	OG	1	1	334.4	10.0	0.0
28	2	Őrtilos	OG	4	4	176.8	10.7	0.0
29	2	Pat	OG	4	2	750.4	29.6	0.0
30	2	Pusztaapáti	O	1	1	512.0	43.4	189.2
31	2	Pusztaszentlászló-Hahót-Sójtör	OG	1	1	1345.8	50.0	662.1
32	2	Pusztaszentlászló-Kelet	OG	2	2	34.4	29.7	2.2
33	2	Sávoly-Dél	OG	2	2	213.9	44.8	80.9
34	2	Sávoly-Délkelet	OG	8	8	3429.3	35.8	747.7
35	2	Sávoly-Nyugat	OG	2	1	1904.8	12.2	127.3
36	2	Somogysámson	OG	1	1	49.1	10.0	0.7
37	2	Tatárvár	O	1	1	1321.8	3.0	8.5
38	2	Újfalu	OG	1	1	960.0	21.9	207.9
39	2	Vízvár	OG	28	4	490.7	13.9	46.9
40	2	Vízvár-sekély	OG	2	1	282.6	17.5	0.1
41	2	Zalakaros-Sávoly	OG	2	2	3433.8	38.7	1191.8
42	2	Zalakomár	OG	1	1	201.7	37.5	61.1
43	3	Algyő	OG	73	36	94561.9	45.0	36668.0
44	3	Ásotthalom	OG	2	1	4091.5	49.5	1847.1
45	3	Ásotthalom-Észak	OG	1	1	2020.2	8.7	121.2
46	3	Bugac	OG	1	1	67.1	40.3	18.0
47	3	Dorozsma	OG	6	6	5152.4	48.0	1787.6
48	3	Eresztő	OG	2	1	341.7	12.5	1.0
49	3	Ferencszállás	OG	25	10	1531.1	37.8	541.4
50	3	Ferencszállás-Kelet- Kiszombor	OG	4	1	1583.8	28.1	438.3
51	3	Forráskút-Sándorfalva	OG	9	2	264.9	30.0	0.1
52	3	Jánoshalma	OG	3	1	23.2	19.8	0.0

Table 7.1. Continues

No	Sub-basin	Oil field	Oil/Gas/CO_2 reservoirs in the field	Number of reservoirs	Number of oil reservoirs in the field	Discovered oil initially in place (kilotons)	Estimated recovery (%)	Total oil production (kilotons)
53	3	Kecel	O	1	1	98.0	10.0	0.0
54	3	Kelebia-Dél	OG	1	1	1586.5	51.0	798.9
55	3	Kelebia-Észak	OG	2	2	798.3	22.3	177.3
56	3	Kiskunhalas kut. terület	O	1	1	0.2		0.2
57	3	Kiskunhalas-Dél	OG	3	1	996.5	25.0	13.1
58	3	Kiskunhalas-É	OG	3	3	127.4	24.6	0.7
59	3	Kiskunhalas-ÉK. metamorf	OG	3	3	5686.2	33.3	1795.2
60	3	Kiskunhalas-ÉK. mezozoos	OG	1	1	1406.0	20.4	279.8
61	3	Kiskunhalas-ÉNy	OG	2	2	313.3	30.5	10.9
62	3	Kiskunmajsa Dél	OG	4	1	379.3	2.4	0.1
63	3	Mélykút-Északkelet	OG	3	2	73.5	25.0	5.5
64	3	Öttömös	OG	2	2	145.9	15.9	12.2
65	3	Öttömös-Kelet	OG	2	2	1401.7	41.2	460.7
66	3	Öttömös-Ny/I.,III.	OG	2	1	36.2	9.9	0.0
67	3	Öttömös-Nyugat	OG	1	1	23.5	25.0	0.0
68	3	Pálmonostora-DNy	O	1	1	303.8	30.0	0.0
69	3	Ruzsa	OG	6	5	1084.8	24.7	213.2
70	3	Szank	OG	4	3	8564.4	33.0	2642.3
71	3	Szank-ÉNy	OG	1	1	716.6	32.7	195.2
72	3	Szank-Nyugat	OG	7	4	126.2	20.0	3.3
73	3	Szeged-Móraváros	OG	2	1	9390.7	81.4	3724.8
74	3	Szentmihálytelek	OG	3	2	360.5	34.7	5.6
75	3	Tázlár	OG	6	4	1326.0	15.3	86.3
76	3	Tázlár-Észak	OG	4	3	595.4	10.8	45.9
77	3	Üllés-mélyszint	OG	16	12	1806.4	25.6	222.0
78	3	Zsana-Észak	OG	1	1	98.1	10.0	0.0
79	4	Battonya	OG	7	1	1866.2	13.9	241.8
80	4	Battonya-Kelet	OG	1	1	4380.0	25.6	1119.6
81	4	Csanádalberti-Észak	OG	2	2	1301.9	30.0	1.4
82	4	Csanádapáca	OG	4	1	268.0	35.0	89.9
83	4	Kaszaper-Dél	OG	2	1	749.2	10.1	34.1
84	4	Magyarbánhegyes	OG	1	1	117.6	20.0	0.2
85	4	Magyarbánhegyes-Kelet	OG	1	1	1050.6	6.7	0.8
86	4	Medgyesbodzás	OG	1	1	270.6	20.0	1.0
87	4	Medgyesegyháza	OG	2	1	65.0	20.0	0.0
88	4	Mezőhegyes	OG	26	2	452.0	47.0	209.6
89	4	Mezőhegyes-Nyugat	OG	9	1	105.0	30.0	0.4
90	4	Nagybánhegyes	OG	1	1	737.9	30.0	6.6
91	4	Pitvaros-Észak	OG	2	2	1158.3	1.9	8.3
92	4	Pusztaföldvár	OG	47	4	6293.2	40.4	2507.5
93	4	Pusztaszőlős	OG	21	1	1440.0	2.3	25.2
94	4	Tótkomlós-Dél	OG	1	1	543.3	8.0	21.9
95	4	Tótkomlós-DNy	OG	1	1	227.6	22.9	50.5
96	4	Tótkomlós-Észak	OG	1	1	106.9	30.0	0.0
97	4	Végegyháza-Nyugat	OG	14	1	43.0	30.0	0.1
98	5	Cegléd	OG	1	1	75.8	10.0	0.3
99	5	Kaba-Észak	OG	4	1	36.4	15.0	0.0
100	5	Karcag	OG	1	1	209.1	5.0	0.0

Table 7.1. Continues

No	Sub-basin	Oil field	Oil/Gas/CO_2 reservoirs in the field	Number of reservoirs	Number of oil reservoirs in the field	Discovered oil initially in place (kilotons)	Estimated recovery (%)	Total oil production (kilotons)
101	5	Nádudvar-DNy	OG	7	1	16.8	20.0	0.0
102	5	Nádudvar-ÉK	OG	6	2	61.4	30.0	0.0
103	5	Nagykőrös	OGC	7	2	316.1	20.9	53.8
104	5	Püspökladány	OG	2	1	152.2	15.0	3.4
105	5	Szolnok	OG	1	1	430.5	36.2	155.7
106	5	Szolnok-III	OG C	4	1	1326.0	10.0	0.0
107	5	Törtel	OG	3	2	28.3	19.8	3.4
108	6	Dévaványa	OG	19	1	81.8	12.0	8.1
109	6	Endrőd-Észak	OG	17	2	710.8	8.8	0.0
110	6	Földes-Nyugat	OG	5	3	161.8	30.0	0.3
111	6	Füzesgyarmat	OC	5	3	631.0	30.0	0.8
112	6	Kaba-Dél	OG	1	1	402.0	40.0	152.8
113	6	Körösladány	OG	2	1	48.2	30.0	0.0
114	6	Martfű-Dél	OG	8	1	162.2	28.0	41.9
115	6	Szeghalom	OG	4	2	4532.6	18.1	795.0
116	6	Szeghalom-Észak-1	OGC	3	2	169.2	30.3	0.2
117	6	Szeghalom-Észak-5	OG	2	1	8.0	30.0	0.2
118	6	Szeghalom-Nyugat	OG	1	1	290.0	12.0	32.6
119	6	Túrkeve-Kelet	OG	17	1	18.1	30.0	0.0
120	7	Álmosd	OG	3	2	38.4	9.1	0.3
121	7	Kismarja	OGC	21	10	1126.8	20.9	185.9
122	7	Kismarja-Dél	OGC	6	2	298.9	9.3	0.1
123	7	Komádi	OG	29	13	2658.5	23.9	9.8
124	7	Mezősas	OG	8	8	2653.5	13.3	187.2
125	7	Mezősas-Nyugat	OG	10	6	6371.5	12.6	202.6
126	7	Okány-3	O	1	1	198.9	13.5	0.0
127	7	Sarkadkeresztúr	OG	5	2	761.4	30.0	207.4
128	8	Hajdúnánás	OG	7	1	19.5	30.0	2.0
129	9	Dány	OG	1	1	478.9	58.3	259.9
130	9	Demjén-Kelet	OG	1	1	6868.6	16.9	1142.6
131	9	Demjén-Nyugat	O	1	1	1053.6	15.0	138.7
132	9	Demjén-Pünkösdhegy	OG	1	1	1159.6	12.6	95.2
133	9	Gomba-D	OG	1	1	336.4	10.6	6.2
134	9	Gomba-É	OG	1	1	2026.8	10.0	1.2
135	9	Gomba-központi	OG	1	1	2429.6	50.6	1122.0
136	9	Mezőkeresztes	OG	3	1	1775.1	9.7	172.3
137	9	Monor-Észak	OG	1	1	342.7	10.9	0.8
138	9	Nagykáta	OG	1	1	621.6	38.3	226.4
139	9	Nagykáta-Nyugat	OG	1	1	361.9	38.8	31.8
140	9	Ócsa	OG	1	1	229.1	48.4	53.8
141	9	Sülysáp-Észak	OG	1	1	359.2	13.6	2.2
142	9	Tóalmás-Dél	OG	5	3	2467.6	30.5	291.6
143	9	Tura	OG	4	3	377.0	18.7	33.8
All together					344 oil reservoirs	331.2 million tons		100.5 million tons

Sorting of oil fields by amount of their resource shows their resource distribution, that is, the range of the size of known fields of Hungary (Figure 7.3).

Discovered resources summarised by every year may predict the efficiency of future explorations (Figure 7.4). These figures shows the tendency which size may forecast in the future exploration areas. The flattening of the recently discovered fields curve in this case means that with known methods and techniques, discovery of smaller and smaller mineral wealth fields is likely in the future.

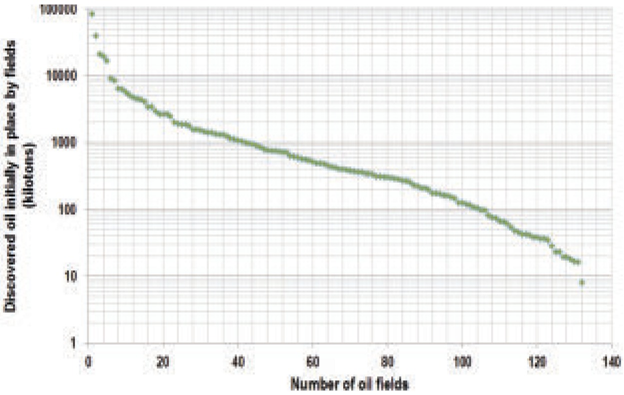


Figure 7.3. Distribution of initially in-place resources of conventional oil fields sorted by decreasing size (kiloton values)

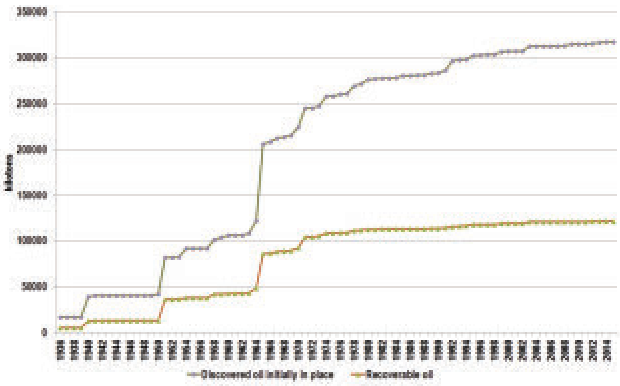


Figure 7.4. Cumulative volume of the in-place and recoverable resources of conventional crude oil discovered to date (kiloton values)

Hungarian combustable natural gas fields and their resources

In the Table 7.2, summarised resource data of 271 crude oil and natural gas fields containing 1,345 combustible natural gas (less than 90% CO_2 gas content) reservoirs is given. Besides resources data, the table specifies the sub-basin in which the field is located, the number of reservoirs in the field that contains combustible natural gas, and whether there are only free gas reservoirs (G) or even oil (O) or carbon-dioxide gas (C) is present in the field. So amount of dissolved gas and cap gas in oil fields is also given. Given quantity of combustable gas resources are also contains the amount of inert gas (CO_2 and N_2) contents.

Table 7.2. Resources data of combustable natural gas fields

No	Sub-basin	Field name	Oil/Gas/CO_2 reservoirs	Number of reservoirs	Number of flammable gas reservoirs	Discovered flammable gas resources initially in place (million m^3)	Estimated recovery (%)	Total flammable gas production (million m^3)
1	1	Celldömölk-ÉNy	G	1	1	53.6	70.0	0.1
2	1	Ikervár	G	4	4	132.5	53.9	0.0
3	1	Pásztori	GC	3	2	16.6	79.5	0.0
4	1	Répcelak mixed gas	G	2	2	1434.3	70.0	601.0
5	1	Tét-3	G	1	1	265.1	60.0	73.2
6	1	Tét-5	G	1	1	14.4	70.1	0.0
7	1	Tét-6	G	1	1	45.8	70.1	0.0
8	1	Uraiújfalu	G	10	10	443.7	52.2	226.8
9	2	Bajánsenye	G	1	1	272.3	58.9	136.9
10	2	Bajcsa	G	1	1	1669.2	29.9	486.8
11	2	Barcs	OG	4	3	200.0	63.6	105.8
12	2	Barcs-Nyugat	G	1	1	1654.9	63.7	796.0
13	2	Belezna	OG	2	0	461.9	73.2	203.3
14	2	Belezna-Dél	OG	3	2	45.7	42.4	0.0
15	2	Belezna-Kelet	G	2	2	9.5	50.0	0.0
16	2	Belezna-Kelet-1	OG	2	0	46.4	29.1	0.0
17	2	Budafa-Kiscsehi	OG	7	0	3941.0	68.2	2689.1
18	2	Budafa-Oltárc	G	2	2	84.5	86.9	15.1
19	2	Csesztreg	G	1	1	280.0	70.0	0.0
20	2	Csombárd	G	4	4	622.3	78.9	0.0
21	2	Darány	OG	3	1	8.6	46.5	0.0
22	2	Görgeteg-Babócsa	OG	15	13	1894.1	78.9	1135.8
23	2	Gutorfölde	G	4	4	351.1	69.8	0.1
24	2	Heresznye	OG	10	6	80.5	74.5	0.7
25	2	Homokszentgyörgy	OG	3	1	64.2	70.1	0.0
26	2	Horvátkút	G	1	1	179.0	61.0	0.0
27	2	Iharosberény	G	1	1	101.3	70.0	0.0

Table 7.2. Continues

No	Sub-basin	Field name	Oil/Gas/CO_2 reservoirs	Number of reservoirs	Number of flammable gas reservoirs	Discovered flammable gas resources initially in place (million m^3)	Estimated recovery (%)	Total flammable gas production (million m^3)
28	2	Inke–Iharosberény–Vése	G	10	10	3456.0	79.3	0.0
29	2	Jánosmajor	OG	2	0	7.4	70.2	2.6
30	2	Kilimán	G	1	1	209.9	60.0	0.0
31	2	Liszó	G	10	10	3449.1	73.4	0.0
32	2	Lovászi	OG	7	2	6290.7	67.9	4272.9
33	2	Mezőcsokonya	GC	13	10	4139.7	55.7	464.1
34	2	Mezőcsokonya-Nyugat	OG	1	0	27.3	17.9	3.5
35	2	Nagybakónak	OG	2	0	16.4	11.4	0.0
36	2	Nagylengyel-Szilvágy-Dél	OG	1	0	91.0	14.5	13.2
37	2	Ortaháza	OG	19	9	1321.5	61.4	347.8
38	2	Ortaháza-Kelet	OG	5	4	194.1	89.7	138.5
39	2	Ortaháza-Nyugat	OG	1	0	7.5	10.1	0.0
40	2	Őriszentpéter-Dél	G	1	1	1407.0	63.3	688.7
41	2	Örtilos	OG	4	0	65.2	49.9	0.0
42	2	Pat	OG	4	2	101.7	76.6	0.0
43	2	Pusztaederics–Hahót–Söjtör	G	2	2	788.0	84.6	401.0
44	2	Pusztamagyaród	G	2	2	14.1	75.0	8.1
45	2	Pusztaszentlászló–Hahót–Söjtör	OG	1	0	46.4	59.5	27.6
46	2	Pusztaszentlászló-Kelet	OG	2	0	0.8	37.5	0.1
47	2	Rádiháza	G	6	6	1193.8	70.0	0.0
48	2	Sávoly-Dél	OG	2	0	11.9	35.2	2.9
49	2	Sávoly-Délkelet	OG	8	0	118.8	42.0	38.0
50	2	Sávoly-Kelet	G	4	4	54.0	70.0	0.0
51	2	Sávoly-Nyugat	OG	2	1	552.2	25.7	8.5
52	2	Somogysimson	OG	1	0	1.3	9.9	0.0
53	2	Somogyudvarhely	G	1	1	4000.0	70.0	0.0
54	2	Szentgyörgyvölgy	G	1	1	333.3	50.0	0.0
55	2	Tófej	G	1	1	79.2	74.7	7.4
56	2	Tófej-Nyugat	G	1	1	74.2	61.1	0.0
57	2	Törökkoppány	G	1	1	245.0	68.2	142.1
58	2	Újfalu	OG	1	0	97.5	75.5	44.1
59	2	Vétyem	G	2	2	73.9	64.5	0.5
60	2	Vétyem-Kelet	G	2	2	155.0	61.6	0.0
61	2	Vízvár	OG	28	24	872.4	49.5	10.8
62	2	Vízvár-Észak	G	1	1	1471.6	32.9	104.2
63	2	Vízvár-sekély	OG	2	1	77.3	67.5	0.0
64	2	Zalakaros–Sávoly	OG	2	0	1061.4	72.9	106.6
65	2	Zalakomár	OG	1	0	10.0	62.6	2.3
66	2	Zaláta	G	2	2	2192.2	78.0	0.0
67	2	Zalatárnok	G	1	1	15.9	61.0	4.6
68	3	Algyő	OG	73	37	118272.8	76.4	82184.9
69	3	Ásotthalom	OG	2	1	193.0	45.2	66.2
70	3	Ásotthalom-Észak	OG	1	0	455.3	63.6	168.9
71	3	Borota	G	1	1	843.9	64.6	122.7
72	3	Bugac	OG	1	0	3.2	31.1	0.7
73	3	Csólyospálos-Kelet	G	1	1	929.0	80.7	663.9
74	3	Dorozsma	OG	6	0	1079.1	53.3	556.0
75	3	Ereszto	OG	2	1	924.5	85.4	744.5
76	3	Ferencszállás	OG	25	15	4269.2	94.0	3708.5
77	3	Ferencszállás-Kelet–Kiszombor	OG	4	3	512.7	73.4	365.3
78	3	Forráskút-D	G	2	2	0.1	100.0	0.1

Table 7.2. Continues

No	Sub-basin	Field name	Oil/Gas/CO_2 reservoirs	Number of reservoirs	Number of flammable gas reservoirs	Discovered flammable gas resources initially in place (million m^3)	Estimated recovery (%)	Total flammable gas production (million m^3)
79	3	Forráskút–Sándorfalva	OG	9	7	474.6	80.7	263.6
80	3	Harka	G	1	1	315.0	49.0	115.3
81	3	Jánoshalma	OG	3	2	1400.0	50.6	663.5
82	3	Jánoshalma-Dél	G	1	1	87.4	49.9	5.6
83	3	Kelebia-Dél	OG	1	0	39.2	62.0	24.1
84	3	Kelebia-Észak	OG	2	0	28.3	26.6	7.2
85	3	Kiskunhalas	G	5	5	596.8	83.0	431.1
86	3	Kiskunhalas ÉK. metamorf	OG	3	0	1105.3	76.4	602.8
87	3	Kiskunhalas ÉK. mezozoos	OG	1	0	1380.4	81.1	1118.9
88	3	Kiskunhalas–15	G	1	1	11.0	74.5	1.1
89	3	Kiskunhalas-Dél	OG	3	2	950.4	74.0	665.0
90	3	Kiskunhalas-É	OG	3	0	9.2	23.9	0.0
91	3	Kiskunhalas-ÉNy	OG	2	0	0.3	100.0	0.3
92	3	Kiskunmajsa	G	2	2	75.6	77.6	33.0
93	3	Kiskunmajsa Dél	OG	4	3	3682.3	78.0	2445.7
94	3	Kömpöc	G	1	1	0.1	100.0	0.1
95	3	Kömpöc-Dél	G	1	1	550.0	99.8	525.3
96	3	Mélykút-Északkelet	OG	3	1	4.6	26.1	0.6
97	3	Mórahalom	G	1	1	162.3	80.0	114.3
98	3	Öttömös	OG	2	0	30.4	20.0	1.1
99	3	Öttömös-Kelet	OG	2	0	24.8	49.4	11.4
100	3	Öttömös-Ny/I.,III.	OG	2	1	25.7	70.0	0.0
101	3	Öttömös-Nyugat	OG	1	0	9.2	75.7	0.0
102	3	Öttömös-Nyugat/2002	G	1	1	59.9	74.1	44.2
103	3	Páhi	G	2	2	86.0	69.7	0.0
104	3	Rém	G	1	1	0.8	75.0	0.0
105	3	Ruzsa	OG	6	1	709.0	52.3	287.1
106	3	Soltvadkert	G	1	1	137.7	79.2	83.2
107	3	Soltvadkert-Kelet	G	1	1	123.4	89.1	94.0
108	3	Szank	OG	4	1	13545.0	79.1	10506.5
109	3	Szank-ÉNy	OG	1	0	32.0	25.1	7.7
110	3	Szank-Nyugat	OG	7	3	571.8	89.9	481.6
111	3	Szeged-Móraváros	OG	2	1	3142.3	43.6	1276.5
112	3	Szentmihálytelek	OG	3	1	144.6	42.0	12.2
113	3	Tázlár	OG	6	2	3466.5	73.8	2930.2
114	3	Tázlár-Észak	OG	4	1	65.1	36.7	5.5
115	3	Tiszakécske	G	1	1	10407.0	75.0	0.0
116	3	Tompa	G	1	1	2.9	69.0	0.0
117	3	Üllés-mélyszint	OG	16	4	16955.8	89.3	14653.1
118	3	Zsana-Észak	OG	1	0	6413.8	87.8	4270.9
119	3	Zsana-Nyugat	G	2	2	14.6	71.2	0.0
120	4	Battonya	OG	7	6	4189.1	73.9	2492.2
121	4	Battonya-Észak	G	1	1	125.0	57.4	56.1
122	4	Battonya-Kelet	OG	1	0	955.3	45.6	419.2
123	4	Battonya-Kelet free gas	G	1	1	11.3	62.0	0.0
124	4	Battonya-Kelet/6002	G	1	1	1.7	0.0	0.0
125	4	Békés	G	2	2	135.0	23.0	0.0
126	4	Csanádalberti-Észak	OG	2	0	232.5	30.0	0.1
127	4	Csanádapáca	OG	4	3	161.9	89.0	89.4
128	4	Kaszaper-Dél	OG	2	1	968.9	60.6	410.9
129	4	Kevermes	G	1	1	19.7	70.1	0.0

Table 7.2. Continues

No	Sub-basin	Field name	Oil/Gas/CO_2 reservoirs	Number of reservoirs	Number of flammable gas reservoirs	Discovered flammable gas resources initially in place (million m^3)	Estimated recovery (%)	Total flammable gas production (million m^3)
130	4	Kunágota	G	6	6	289.1	72.1	98.1
131	4	Magyarbánhegyes	OG	1	0	329.1	82.4	0.0
132	4	Magyarbánhegyes-Dél	G	1	1	329.1	82.4	18.3
133	4	Magyarbánhegyes-Kelet	OG	1	0	64.2	7.2	0.0
134	4	Magyardombegyház-DNy	G	3	3	252.2	70.8	59.6
135	4	Medgyesbodzás	OG	1	0	4.8	20.0	0.2
136	4	Medgyesegyháza	OG	2	1	35.3	69.4	0.0
137	4	Mezőhegyes	OG	26	24	1103.4	64.4	479.3
138	4	Mezőhegyes-DK	G	2	2	217.2	65.8	14.2
139	4	Mezőhegyes-Nyugat	OG	9	8	1172.7	68.0	657.9
140	4	Nagybánhegyes	OG	1	0	35.5	30.0	1.2
141	4	Nagybánhegyes free gas	G	1	1	17.6	70.0	0.0
142	4	Pitvaros-Észak	OG	2	0	62.2	2.1	0.8
143	4	Pusztaföldvár	OG	47	43	17548.9	75.4	12128.5
144	4	Pusztaföldvár-Észak	G	2	2	83.6	40.1	2.0
145	4	Pusztaszőlős	OG	21	20	2443.2	72.7	1395.7
146	4	Tompapuszta	G	7	7	116.8	48.7	3.5
147	4	Tótkomlós	G	24	24	1060.3	81.6	753.8
148	4	Tótkomlós-Dél	OG	1	0	44.8	15.3	1.9
149	4	Tótkomlós-DNy	OG	1	0	24.5	57.1	13.3
150	4	Tótkomlós-Észak	OG	1	0	1.9	30.3	0.0
151	4	Tótkomlós-Kelet	G	3	3	96.4	69.5	23.3
152	4	Végegyháza-Nyugat	OG	14	13	814.1	67.8	424.7
153	5	Ebes	G	7	7	687.2	87.4	550.1
154	5	Ebes-É	G	2	2	53.1	70.0	0.0
155	5	Egyek	G	1	1	15.1	50.0	0.0
156	5	Fegyvernek	G	17	17	2730.9	53.0	1083.2
157	5	Hajdúszoboszló	G	19	19	37778.5	83.8	29034.0
158	5	Kaba	G	1	1	116.0	70.0	80.2
159	5	Kaba-Észak	OG	4	3	106.6	66.1	49.0
160	5	Karcag	OG	1	0	9.7	5.1	0.0
161	5	Karcag–Bucsa	G	5	5	711.9	81.6	210.4
162	5	Kenderes-Dél	G	1	1	64.6	75.0	0.0
163	5	Kengyel-Észak–1	G	3	3	130.2	60.4	18.3
164	5	Kisújszállás-ÉK	G	1	1	19.8	70.0	0.0
165	5	Kisújszállás-K	G	4	4	200.0	58.5	110.4
166	5	Kisújszállás-Nyugat	G	19	19	6945.5	83.3	5077.3
167	5	Nádudvar-DNy	OG	7	6	169.0	69.2	45.8
168	5	Nádudvar-ÉK	OG	6	4	213.0	62.1	0.0
169	5	Nagykőrös	OGC	7	0	64.0	78.6	0.0
170	5	Nagykőrös-Dél	G	6	6	1041.4	52.6	0.0
171	5	Nagykőrös-Dél-Kecskemét	G	4	4	52.5	67.1	0.0
172	5	Nagykörü	GC	20	19	6921.9	60.9	2907.7
173	5	Nagykörü-Ny	GC	8	6	837.7	67.9	272.9
174	5	Örményes-Délkelet	G	2	2	727.6	74.8	0.0
175	5	Örményes-Kelet	G	2	2	547.1	79.3	3.0
176	5	Penészlek	G	2	2	104.0	55.0	54.0
177	5	Penészlek (határmenti)	G	3	3	334.2	76.5	157.5
178	5	Püspökladány	OG	2	1	3442.3	64.5	0.4
179	5	Szandaszőlős	G	4	4	881.5	68.7	182.6
180	5	Szolnok	OG	1	0	29.5	42.9	12.7

Table 7.2. Continues

No	Sub-basin	Field name	Oil/Gas/CO_2 reservoirs	Number of reservoirs	Number of flammable gas reservoirs	Discovered flammable gas resources initially in place (million m^3)	Estimated recovery (%)	Total flammable gas production (million m^3)
181	5	Szolnok-Délnyugat	G	1	1	7.0	73.0	0.0
182	5	Szolnok- Hajtótanya	G	1	1	35.9	73.0	0.0
183	5	Szolnok- III	OGC	4	0	43.5	10.0	0.0
184	5	Tatárülés- Kunmadaras	G	3	3	4222.7	79.4	2893.1
185	5	Tiszagyenda	G	1	1	50.5	70.0	0.0
186	5	Tiszapüspöki	G	2	2	87.6	81.0	14.4
187	5	Tiszaszentimre	G	2	2	92.8	69.2	25.0
188	5	Tószeg	G	3	3	92.2	73.0	0.0
189	5	Törökszentmiklós	G	4	4	82.3	80.2	22.4
190	5	Törökszentmiklós-Dél	G	2	2	112.8	70.0	0.0
191	5	Törtel	OG	3	1	14.7	80.3	3.0
192	5	Turgony	G	1	1	6.4	79.2	0.0
193	5	Túrkeve-Nyugat	G	4	4	369.3	70.7	6.9
194	5	Zagyvarékas-Észak	G	1	1	900.1	85.3	0.0
195	6	Berettyóújfalu	G	6	6	237.5	10.0	0.0
196	6	Dévaványa	OG	19	18	913.0	72.8	464.2
197	6	Dévaványa-Dél	G	4	4	847.0	75.9	568.6
198	6	Dévaványa-Kelet	G	5	5	245.4	81.3	174.5
199	6	Endrőd-Észak	OG	17	15	2271.9	67.9	820.6
200	6	Endrőd- I	G	22	22	1951.1	78.4	1207.2
201	6	Endrőd- III	G	27	27	6399.3	81.4	4655.6
202	6	Endrőd- III/C	G	4	4	532.7	74.2	5.8
203	6	Endrőd-Kelet	G	1	1	121.8	75.8	46.7
204	6	Földes-Kelet	G	8	8	8343.7	44.5	1998.5
205	6	Földes-Nyugat	OG	5	2	1158.8	69.0	100.2
206	6	Hajdúbagos-Kelet	G	19	19	276.6	63.4	0.5
207	6	Hosszúpályi-Dél	G	24	24	4932.3	68.3	2122.7
208	6	Kaba-Dél	OG	1	0	71.0	45.0	26.3
209	6	Körösladány	OG	2	1	227.3	65.2	0.0
210	6	Köröstarcsa	G	2	2	464.1	31.1	0.0
211	6	Martfű-Dél	OG	8	7	1544.1	79.5	756.4
212	6	Martfű-Észak- II	G	2	2	150.3	80.0	36.5
213	6	Mezőtúr	G	1	1	180.9	49.8	25.4
214	6	Monostorpályi-Kelet	G	1	1	43.1	65.0	4.1
215	6	Öcsöd	G	3	3	285.4	66.2	0.4
216	6	Sáránd	G	1	1	63.7	70.0	0.0
217	6	Sáránd-sekély	G	2	2	91.5	70.0	0.0
218	6	Szarvas	G	12	12	4405.2	70.7	1344.6
219	6	Szeghalom	OG	4	2	11031.3	64.9	7049.3
220	6	Szeghalom-Észak- 1	OGC	3	0	11.3	37.8	1.3
221	6	Szeghalom-Észak- 5	OG	2	1	167.2	74.3	120.3
222	6	Szeghalom-Nyugat	OG	1	0	174.4	50.6	84.4
223	6	Túrkeve-D	G	1	1	402.0	37.8	120.6
224	6	Túrkeve-ÉK	G	3	3	54.8	70.1	20.3
225	6	Túrkeve-ÉNy	G	3	3	624.5	70.0	235.3
226	6	Túrkeve-Kelet	OG	17	16	970.2	69.8	172.7
227	7	Álmosd	OG	3	1	525.9	79.1	139.8
228	7	Álmosd- 4	G	2	2	9.4	60.0	0.0
229	7	Álmosd-Észak	G	12	12	91.4	61.4	17.0

Table 7.2. Continues

No	Sub-basin	Field name	Oil/Gas/CO_2 reservoirs	Number of reservoirs	Number of flammable gas reservoirs	Discovered flammable gas resources initially in place (million m^3)	Estimated recovery (%)	Total flammable gas production (million m^3)
230	7	Berettyószentmárton	G	1	1	64.8	70.0	0.0
231	7	Berettyószentmárton-Dél	GC	4	3	223.9	51.7	0.0
232	7	Biharkeresztes	G	9	9	5373.5	70.3	403.5
233	7	Furta-Észak	G	1	1	34.6	45.0	0.0
234	7	Furta-Zsáka	GC	18	16	1411.6	66.2	401.4
235	7	Kismarja	OGC	21	4	54.7	22.4	11.6
236	7	Kismarja-Dél	OGC	6	2	221.1	71.1	3.3
237	7	Kismarja-Nyugat	G	5	5	309.2	67.3	139.9
238	7	Kokad	G	3	3	18.4	70.0	0.0
239	7	Komádi	OG	29	16	1657.6	68.8	420.9
240	7	Kótpuszta	G	5	5	89.0	73.3	22.4
241	7	Körösújfalu-I	G	3	3	1762.2	72.9	841.2
242	7	Körösújfalu-II	G	3	3	282.0	65.6	57.0
243	7	Létavértes	G	25	25	424.5	57.7	26.2
244	7	Mezőpeterd	GC	7	5	973.9	70.0	79.5
245	7	Mezősas	OG	8	0	578.6	16.8	42.2
246	7	Mezősas-Nyugat	OG	10	4	6423.2	51.1	205.4
247	7	Nagykereki-Nyugat	G	2	2	43.3	70.0	0.0
248	7	Nyékpuszta	G	1	1	419.0	57.5	0.0
249	7	Okány-1	G	1	1	95.1	62.4	18.4
250	7	Sarkadkeresztúr	OG	5	3	5501.7	84.1	4376.7
251	7	Vésztő	G	1	1	144.1	60.0	0.0
252	7	Zsadány-Észak	G	2	2	322.1	49.7	117.1
253	8	Hajdúnánás	OG	7	6	248.9	70.2	174.7
254	9	Dány	OG	1	0	0.4	84.6	0.0
255	9	Demjén-Kelet	OG	1	0	412.0	32.8	135.3
256	9	Demjén-Pünkösdhegy	OG	1	0	17.6	60.0	1.1
257	9	Farmos	G	4	4	31.4	86.5	0.0
258	9	Fedémes	G	2	2	66.8	71.9	44.3
259	9	Gomba-D	OG	1	0	12.2	10.5	0.0
260	9	Gomba-É	OG	1	0	143.9	10.0	0.1
261	9	Gomba-központi	OG	1	0	114.0	50.9	44.9
262	9	Mezőkeresztes	OG	3	2	277.9	96.9	269.3
263	9	Mogyoród	G	4	4	421.6	41.2	0.0
264	9	Monor-Észak	OG	1	0	2.0	10.7	0.0
265	9	Nagykáta	OG	1	0	59.5	39.3	22.0
266	9	Nagykáta-Nyugat	OG	1	0	25.5	37.1	1.5
267	9	Ócsa	OG	1	0	3.5	48.9	0.7
268	9	Sülysáp-Észak	OG	1	0	21.5	1.3	0.0
269	9	Tóalmás-Dél	OG	5	2	852.5	46.5	52.7
270	9	Tura	OG	4	1	64.0	58.0	12.4
All together					988 flammable gas reservoirs	426.0 billion m^3		236.2 billion m^3

Sorting of natural gas fields by amount of their resources shows their size distribution (Figure 7.5). Already discovered natural gas fields resources summarised by every year may predict the efficiency of future exploration (Figure 7.6). This trend can be broken with the production of discovered and prospective resources of unconventional hydrocarbon accumulations.

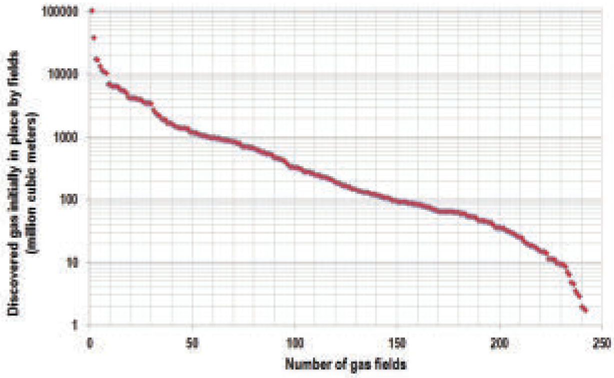


Figure. 7.5. Distribution of initially in-place resources of conventional natural gas fields sorted by decreasing size (million m³ values)

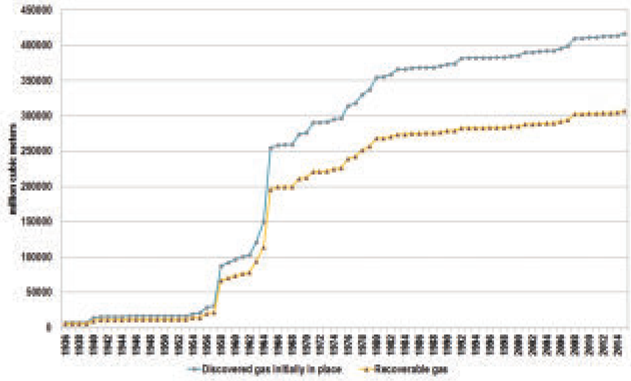


Figure 7.6. Cumulative volume of the in-place and recoverable resources of conventional natural gas discovered to date (million m³ values)

Occurrences of CO_2 gas in Hungary and its resources

In Table 7.3 summarised resources data of 29 hydrocarbon- or CO_2 fields, containing 74 CO_2 natural gas reservoirs is given. Certain fields contain only CO_2 accumulations, while others may contain crude oil or combustible natural gas reservoirs as well. Table shows how many reservoirs can be found in each field and from them how many is a CO_2 gas containing reservoir.

Table 7.3. Fields containing CO_2 reservoirs in Hungary and their resources

No	Sub-basin	Field name	Oil/Gas/CO_2 reservoirs	Number of reservoirs	Number of carbon-dioxide gas reservoirs	Discovered carbon-dioxide gas resources initially in place (million m³)	Estimated recovery (%)	Total carbon-dioxide gas production (million m³)
1	1	Hegyfalu	C	1	1	225.3	60.0	0.0
2	1	Mihályi	C	15	15	7881.7	70.0	1303.3
3	1	Mihályi-Dél	C	1	1	103.5	70.0	0.0
4	1	Ölbö	C	1	1	4438.0	87.5	417.2
5	1	Pásztori	GC	3	1	819.5	80.0	0.0
6	1	Répcelak	C	10	10	4784.3	70.0	1720.7
7	2	Budafa-mélyszint CO_2	C	1	1	17 610.0	65.0	5823.7
8	2	Mezőcsokonya	GC	13	3	2564.4	89.3	0.0
9	2	Pátró	C	2	2	88.4	70.0	0.0
10	5	Cegléd	OC	1	0	4.1	9.8	0.0
11	5	Jászkarajenő	C	1	1	33.5	80.0	0.0
12	5	Kengyel	C	1	1	198.8	70.0	0.0
13	5	Nagykörös	OGC	7	5	2083.6	78.9	369.8
14	5	Nagykörü	GC	20	1	38.0	75.0	0.0
15	5	Nagykörü-Ny	GC	8	2	369.9	81.0	0.0
16	5	Rákóczifalva	C	2	2	4012.1	90.1	27.7
17	5	Szolnok-III.	OGC	4	3	554.1	70.0	0.0
18	5	Újszilvás	C	1	1	509.2	80.0	0.0
19	5	Zagyvarékas	C	1	1	194.3	87.4	0.0
20	6	Füzesgyarmat	OC	5	2	5801.7	61.2	3.9
21	6	Örménykút	C	1	1	467.6	69.9	0.0
22	6	Szeghalom-Észak-1	OGC	3	1	160.0	70.0	0.0
23	7	Berettyószentmárton-Dél	GC	4	1	581.7	0.0	0.0
24	7	Biharugra	C	2	2	205.8	65.0	0.0
25	7	Furta-Zsáka	GC	18	2	250.9	70.0	0.0
26	7	Kismarja	OGC	21	7	565.3	53.3	188.6
27	7	Kismarja-Dél	OGC	6	2	106.9	70.1	0.0
28	7	Mezőpeterd	GC	7	2	69.3	70.0	0.0
29	9	Szécsény	C	2	2	29.9	70.0	0.0
All together					74 carbon-dioxide gas eservoir	54.8 billion m³		9.9 billion m³

There are accumulations where CO_2 is present as a dissolved gas in crude oil or as a cap gas. Purest CO_2 gas is used in the food industry or may serve as a gas injection to increase crude oil enhanced production in certain fields.

Discovered initially in-place CO_2 resources were 54.8 billion m^3, from which 9.75 billion m^3 have been already produced.

Unconventional natural gas and gas condensate occurrences and their resources

The number of registered unconventional hydrocarbon occurrences was 9 in 2016, not including the occurrence and resource of Tiszavasvári. In-place resources are listed in Table 7.4. In contrast to conventional accumulations, recoverable amount is highly dependent on production technology. Table 7.5 contains the estimated gas condensate testified to in the Makó Trough. The all effectively produced amount in Hungary is low, only 40 million m^3 natural gas and 100 tons of gas condensate.

Table 7.4. Unconventional hydrocarbon occurrences and their resources

No	Sub-basin	Unconventional gas mining plot area	Number of gas contained levels	Discovered gas resources initially in place (billion [!] m^3)	Estimated recovery (%)	Total gas production (million [!]m^3)
1	3	Balotaszállás-Deep	4	103.4	10.0	1.6
2	3	Hódmezővásárhely	2	481.1	9.8	0.0
3	3	Makó	2	183.5	15.0	0.0
4	3	Makó Trough I	3	2771.7	51.2	0.1
5	3	Mindszent	3	201.1	9.8	0.0
6	4	Szabadkígyós	1	47.8	10.0	0.0
7	5	Berettyóújfalu	7	25.1	10.0	37.4
8	5	Gyulavári	2	109.5	31.5	0.0
9	5	Nyékpuszta	1	3.3	25.0	0.0
All together			25 levels	3926.4 billion m^3		39.1 million m^3

Table 7.5. Unconventional gas condensate accumulation and its resource

No	Sub-basin	Gas condensate mining plot area	Number of levels	Discovered gas condensate resources initially in place(million [!] tons)	Estimated recovery (%)	Total gas condensate production (thousand [!] tons)
1	3	Makó Trough 1.	3	418.9	10.9	0.1

Most of the gas was produced from the low porosity Middle Miocene tight sandstones of Derecske Trough through using overpressured water hydraulic fracturing technique.

Accumulation explored with Tiszavasvári–6 well is not in the registry, which has a resource of 2 billion m^3, and half of this amount is estimated to turn into production.

Legal aspects

Imre Veres

Pursuant to Act XLVIII of 1993 on Mining (hereinafter: the Mining Act), mineral resources and geothermic energy are owned by the Hungarian State (hereinafter state) as they are found in nature. Therefore, the state generally grants exploration rights regarding mineral resources in concession agreements. The state also grants permits for the exploration and the appraisal of mineral resources it does not wish to explore and appraise in the framework of concession.

The exploration, appraisal and production of hydrocarbon mineral resources may take place within the framework of a concession agreement. The Minister in Charge of National Development is required to publish a public tender for the conclusion of concession agreements.

Concession agreements may be concluded for a period of no more than 35 years and may be extended once with at least half of the original term of the concession agreement. The parties of the concession agreement need to agree on details of the exploration work programme and the legal instruments securing the performance of the same.

For the performance of mining activity subject to concession rights, a concession fee must be paid to the state or other consideration must be provided.

In the case of mining activity carried out based on a permit, the approval process consists of several steps in compliance with the Mining Act. The detailed rules regulating the approval process are specified in Government Decree No. 203/1998. (XII. 19.) implementing Act XLVIII of 1993 on Mining (hereinafter: Government Decree Implementing the Mining Act).

The main steps are as follows:

1) Right to exploration, exploration permit.

2) The application for the designation of the mining site may be submitted in the possession of the final exploration report prepared as a result of the exploration. However, it must be preceded by an environmental protection approval process. That may be a time-consuming process and is subject to a separate administrative fee, as it is not the responsibility of the mining authority.

3) The designation of the mining site may be a result of a two to three year-long approval process depending on the problems or deficiencies occurring during the same (all of these may prolong the process).

– Mineral resources may be explored and exploited, and geological structures may be used for the underground storage of hydrocarbon only on mining sites, which pertain to the surface and depth of the land designated for such purposes;

  – The mining authority will make decisions regarding the mining sites upon applications for mining sites used for opencast workings, taking into consideration the expected exploitation schedule of the real properties constituting a mining site, as well as the remarks of the owners of the real properties regarding the right of use, exploitation and disposition of the real properties,

  – Only the licensee of the mining site may be granted a permit for the development and exploitation of mineral resources and the underground storage of hydrocarbon,

– The exploration and production of mineral resources may be commenced in the possession of a licensed mining site (Paragraph [1] of Section 23 of the Mining Act), for which an approved production engineering and operating plan is also required.

4) The mining contractor will have to commence its mining activities within five (5) years based on the approved production engineering operating plan.

5) The mining activity is subject to operating rules.

6) The mining activity may be suspended.

7) The mining contractor has to gradually restore the surface area which cannot be used as a result of mining (or geological exploration) and enable recultivation by restoring the natural environment. This activity requires spatial planning, which has to be carried out in accordance with the provisions of the Mining Act.

8) Damages caused by mining activity include the following in accordance with Section 37 of the Mining Act:

– Damage caused to real properties, buildings and other components and accessories of the same arising from mining and geological exploration activity, as well as damages caused as a result of dewatering, including any expenditures regarding the prevention, mitigation and averting of damages;

– The mining contractor is required to pay compensation for the damages specified in the laws (mining damages). The mining compensation will have to be paid in monetary form, unless otherwise agreed upon by the parties involved.

– The mining contractor is to seek to reach a settlement regarding compensation. If it cannot reach a settlement, the mining contractor has to pay an amount of compensation justified by an expert opinion within thirty days from the due date of the compensation to the damaged party;

– It is important to note that the damaged party may enforce its claims if not satisfied within the set deadline as well as any other claims exceeding the already paid amounts of compensation by initiating a civil action against the mining contractor.

9) Further legal criteria

Transfer of mining rights:

Mining rights may be transferred upon request, pursuant to the provision of the Mining Act. The transfer of rights acquired based on a permit is subject to the consent of the mining authority, and the consent of the minister is required for the transfer of concession activity.

The laws pertaining to opening a mine are accessible at http://mbfsz.gov.hu under "Laws". However, in addition to the basic laws pertaining to mining activity, it is also important to be familiar with the relevant sectoral rules, as the requirements in terms of civil procedure pertaining to mining activity are included in such rules.

Concession tendering

Lajos Ó. Kovács, György Gyuricza

Pursuant to the Mining Act, in a closed area mineral resources may be explored, developed and exploited, and geothermal energy may be explored, recovered and utilised in the framework of a concession agreement concluded between the minister in charge of mining and a domestic or foreign natural person or a transparent business organisation. Areas qualified by the mining authority as closed areas and favourable for exploiting mineral resources or recovering geothermal energy for energetic purposes may be considered as areas to be used for mining in a concession framework.

Since the Mining Act was published, the mining authority designated closed areas for the mining of different mineral resources; however, the mining authority generally did not take advantage of this option, i.e. the concession, before 2010. Since 2010, several closed areas have been designated, and also in 2010, the Mining Act declared the section of Earth's crust below a depth of 2,500 metres from the ground to be a closed area for geothermic purposes throughout the entire country. In terms of hydrocarbons (and several other minerals), currently the entire area of the country is closed. A notice by the Hungarian Office for Mining and Geology (predecessor of the Mining and Geological Survey of Hungary) on the designation of closed areas was published on 30 November 2016 in the Issue 59 of the Official Gazette of Hungary (Hivatalos Értesítő).

Table 9.1. Some of the main data of the hydrocarbon concession tenders (as of October 5, 2018)

Year	2013	2014	2015	2016	2017	2018
Number of blocks tendered out	4	6	9	9	9	9
Number of blocks tendered for	3	5	8	6	5	5
Names of blocks tendered out (set in bold: those tendered for)	**Battonya–Pusztaföldvár-D** **Battonya–Pusztaföldvár-É** Szegedi-medence-DK **Szegedi-medence-Ny**	**Ebes** **Nagylengyel-Ny** **Nádudvar** **Okány-K** Okány-Ny **Újléta**	**Battonya–Pusztaföldvár-É** **Berettyóújfalu** **Dány** **Lakócsa** **Mogyoród** **Nagykáta** **Ócsa** **Püspökladány** Sellye	**Bázakerettye** **Bucsa** Heves **Jászárokszállás** Köröskladány **Mezőtúr** **Okány-Ny** Zala-K **Zala-Ny**	**Békéssámson** *(=Csanádpalota+Nagyszénás)* **Drávapalkonya** *(=Drávaszabolcs+Sellye)* Fedémes Hatvan Körösladány **Őrség** **Somogyvámos** *(=Mezőcsokonya+Somogyvár)* **Somogybükkösd** *(=Becsehely+Somogyszob)* Tab	**Békéscsaba** *(=Békés+Elek)* **Dráva** **Körösladány** **Szeged-Délkelet** Tard **Tiszafüred** Tiszatarján *(=Tiszacsege+Sajószöged)* Újszilvás Zalaerdőd *(=Rába+Káld)*
Number of valid tenders	4	7	17	10	6	5
Number of contracted blocks	2	5	8	6	5	
Contracted block / granted company	Battonya–Pusztaföldvár-D / Vermilion* Szegedi-medence-Ny / MOL	Ebes / Vermilion Nagylengyel–Ny / HHE Nádudvar / O&GD Okány-K / MOL Újléta / O&GD	Battonya–Pusztaföldvár-É / MOL Berettyóújfalu / O&GD Dány / MOL Lakócsa / HHE Mogyoród / O&GD Nagykáta / O&GD Ócsa / O&GD Püspökladány / PanBridge	Bázakerettye / MOL Bucsa / MOL Jászárokszállás / MOL Mezőtúr / MOL Okány-Ny / MOL Zala-Ny / MOL	Békéssámson / Vermilion Drávapalkonya / HHE Őrség / MOL Somogyvámos / MOL Somogybükkösd / MOL	

*For simplicity, the common short names of the companies are used.

The concession activity, which has been flourishing recently, was triggered by the ("first round") tenders published in 2013. Some of the main data of the tenders are specified in Table 9.1 broken down to years (see also Figure 9.1).

The calls for tenders have been and are published in the Official Journal of the EU, on the website of the Ministry for Innovation and Technology (earlier: Ministry for National Development) and the Mining and Geological Survey of Hungary (earlier called the Hungarian Office for Mining and Geology), as well as in two Hungarian daily newspapers. The tenders are issued by the Minister for Innovation and Technology (earlier called the Minister for National Development), as the minister in charge of mining issues, on behalf of the Hungarian State in compliance with Act CXCVI of 2011 on National Assets, Act XVI of 1991 on Concessions, and the Mining Act, for the exploration, appraisal and production of hydrocarbon in the framework of concession agreements. The execution and assessment of tenders,

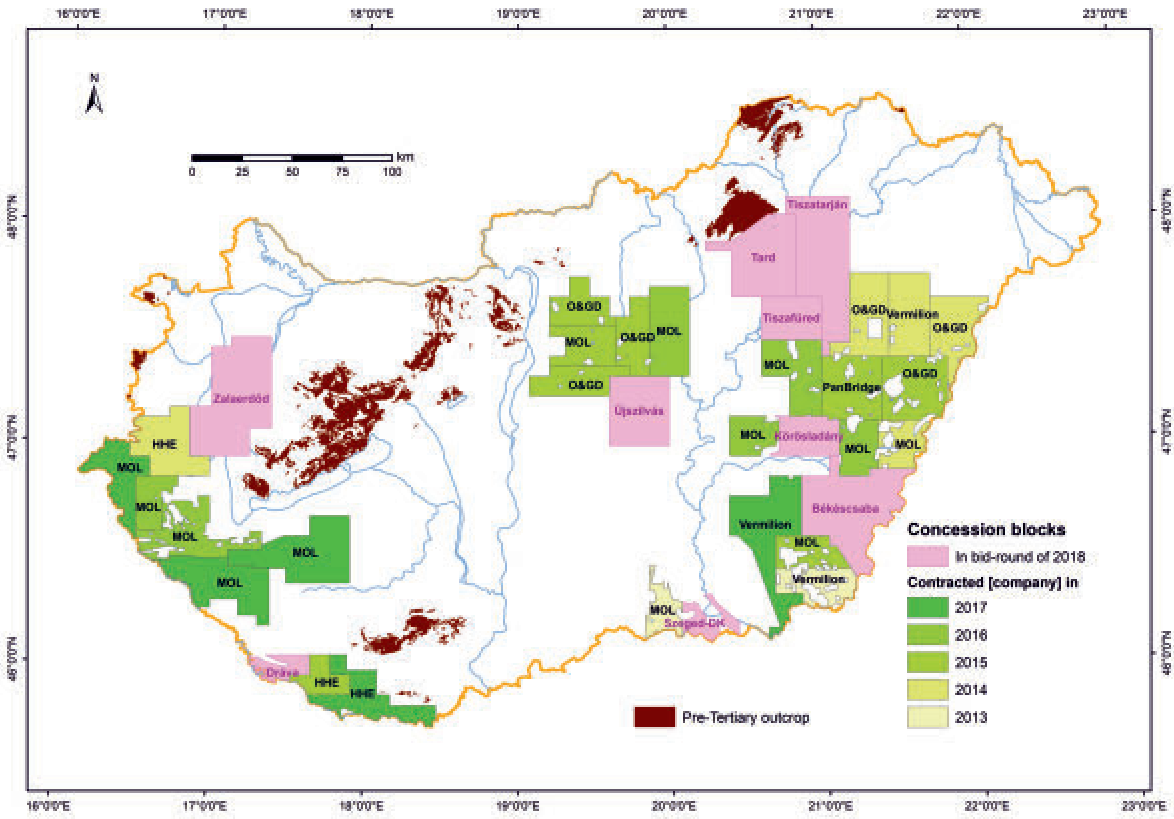


Figure 9.1. Draft map of concession blocks (as of June 26, 2018)

the conclusion of concession agreements for the granted areas, and the inspection of compliance with the agreements are performed in keeping with the relevant provisions of Government Decree No. 203/1998. (XII. 19.) on the implementation of the Mining Act, and Ministerial Decree No. 8/2014 NFM on the mining concession tender procedure.

In order to provide an overall picture of future tender possibilities, a mandatory task required for the preparation of concession areas must be presented. Pursuant to Government Decree No. 103/2011 (VI. 29.) on Complex vulnerability and loading capability assessment of occurrences of mineral resources and geothermal energy (hereinafter: Kétv.), "*a complex vulnerability and loading capability assessment shall be carried out prior to the announcement of an area of occurrence of mineral resources and geothermal energy in a concession tender*." The purpose of the assessment is to determine the areas and spaces where mining activity cannot be pursued, as well as to determine the criteria to be set out in the call for tenders for pursuing mining activity, in order to prepare the decision concerning the subject of the concession tender. The following aspects should be taken into consideration:

– environment, landscape and nature protection,
– water management and water protection,
– cultural heritage protection,
– land protection,
– public health and health protection,
– national security,
– settlement planning,

– transport, and
– management of mineral resources.

In accordance with Kétv., carrying out the assessment may not grant exemption from the obligation to carry out the approval processes necessary for the commencement of the activity, and the cooperating public administration body is not bound by the opinion it provided in the course of the assessment in approving the activity.

The Mining and Geological Survey of Hungary carries out the assessment and prepares the report in cooperation with the Herman Ottó Intézet Nonprofit Kft. and the General Directorate of Water Management, as well as other public administrative bodies and other bodies set forth in Kétv. The city administrators of the municipalities are amongst the members of such bodies in all cases. The Mining and Geological Survey of Hungary performs the assessment for the areas and space-parts where the exploitation of mineral resources or the recovery of geothermal energy for energetic purposes is deemed promising, taking into consideration the available geological data and the potential tenderers' suggestions.

The first series of vulnerability assessments carried out in accordance with the provisions of Kétv. were focusing on geothermal energy. Although the structure of these assessments aimed to follow the subjects provided by the Government Decree, it still deviated from them due to the novelty of the task and some field-specific features. The first classically structured assessment regarding hydrocarbon was accomplished in January 2012. In this case, we finally succeeded in meeting essentially all the requirements set forth by the Government Decree. Subsequently, assessments were prepared in accordance with this scheme.

When preparing the first assessments, the problem was that the topics of the assessment also concern fields of expertise that do not belong to the scope of activities of the institutions preparing the assessment which had to be tackled. There are seven topics of this kind listed amongst Points *a)–i)* of Paragraph (2) of Section 1 of Kétv. (environment, landscape and nature protection, cultural heritage protection, land protection, public health protection, national security, settlement planning and transportation). However, only transportation received a greater role in the requirement set forth in Attachment 2 of the Government Decree regarding the content (*"2.3. General description of the possible connected activities").* The description pertaining to Section 3.1 *("determining the features of the area or space-part that could have a significant influence on the activity")* allowed the comprehensive elaboration of the information related to the other fields of expertise.

When planning the compilation and editing of the assessments, we took into consideration that pursuant to Attachment 1 of Kétv., the cooperating authorities must make a statement regarding the specified topics. Therefore, inevitably, a primary material was prepared by the contributing institutions in topics more or less out of their scope of expertise during the preparation of the first assessments. This did not (could not) lead to impeccable contributions in many cases in terms of the given subject, however, it provided an excellent basis for the authorities to express their opinions. As a result, the texts were revised in the first advising rounds, and we could implement the corrections and amendments, which, with the necessary updates, form an integral part of the assessments also today.

We must not forget the fact that although Attachment 1 of Kétv. specifies the authorities that must provide data or must express opinions and the relevant topics in which data must be provided or opinions must be expressed, it does not include any requirements in terms of the method of communication. Therefore, the authority may decide in what division and in how much detail it provides the necessary information. The quantity and the structure of opinions are different in each field of expertise. At the same time, there may also be significant differences amongst the statements within a single field; the volume of opinions may vary from one or two paragraphs to lists of tens of pages. Therefore, the preparatory text produced by the above mentioned institutions and preliminarily incorporated into the assessment studies has a significant role in keeping the structure proportionate, thus, it also fulfils a moderating function. On the other hand, owing to the subsequent accurate work of the authorities, it ensures professionally substantiated information for the call for tenders.

Based on the assessment of the more than 3,000 authority opinions received until the middle of 2018, it can be concluded that a constructive collective work in compliance with the provisions of Kétv. has been elaborated between the institutions preparing the assessments and the cooperating authorities advising on the same. It might also pose problems, primarily for the municipalities of the settlements, that the assessment in question is not an impact assessment, but vulnerability and loading capability assessment. As a result, the assessments are pertaining to large areas (generally areas of approx. 1,000 km^2), without exact exploration or mining locations. Also, they cannot include exact information concerning the technology and volume of the future exploration and exploitation. This circumstance might cause problems in assessing the expected consequences for the authorities protecting the environmental or historical values under their scope or managing economic assets.

The authorities disposing of the areas in the close environment of the previous exploration and production areas, or concerned by the same, generally have exact information pertaining to the type of the planned concession activity. More uncertainty can be detected in the answers where there have not been any similar activities yet.

All in all, it can be concluded that the requirements of Kétv. are consistently satisfied both in the materials of the assessments and in the final assessment reports also including the opinions of authorities. The vulnerability and loading capability assessments present the data of the areas selected for concession in terms of geography, geology, geology of mineral deposits and hydrology, and the economic significance of the planned activity, on the one hand, while the

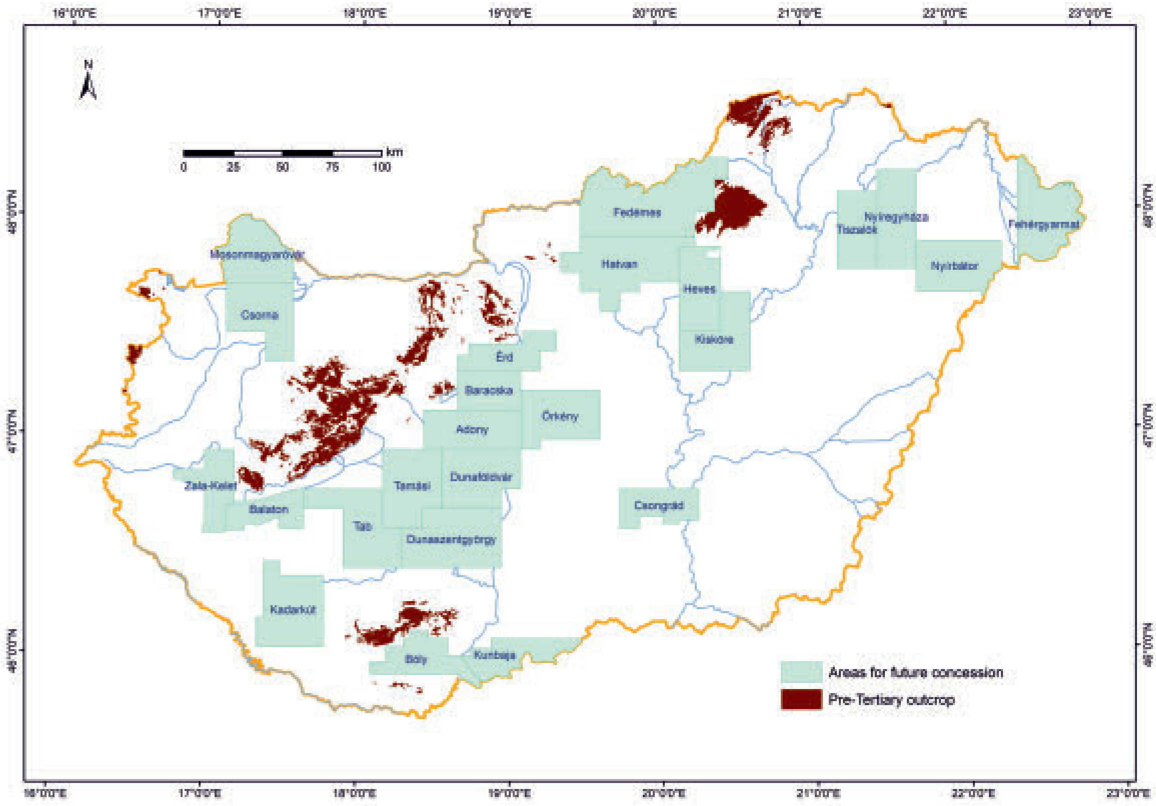


Figure 9.2. Draft map of areas subjected to complex vulnerability and loading capability assessment (as of June 26, 2018)

participation of authorities in carrying out the activity, on the other. The online publication and availability of the reports ensures publicity on a continuing basis, allowing the professional and official as well as the civil sphere concerned by the concession activity to be in contact with each other.

Currently (June 26, 2018), there are 24 areas with completed complex vulnerability and loading capability assessment reports available (Figure 9.2), for which tenders can be published in the future, and there are others under preparation and planning at the Geological and Mining Survey of Hungary. Unless the relevant laws change in general, announcement of further mining concession blocks can be expected in the upcoming years, too.

Infrastructure

Tamás Müller

10

Introduction

Hydrocarbon-exploration and production can be performed on the areas granted on concession bid rounds (‘tenders’) pursuant to the decision of the competent minister’s concessions, and in conformity with the mining rights acquired through these concession processes. Accessibility of the area on road or at railway is of outstanding importance for companies engaged in such future exploration and production, both during exploration and production phases as well. Transportation of experts and crew, as well as technical equipment and other materials required for exploration and production in the relevant area needs a robust transport infrastructure. This can be ensured by road, railway, as well as — in the case of relevant port infrastructure — waterways.

Hungary’s road, railway and water transportation as they relate to aspects of hydrocarbon exploration and production

During the second half of the 19th century, establishment of road and railway infrastructure as well as further development of the existing road and railway network formed the basic condition for the industrialisation of Hungary. In this phase (just like nowadays) the country’s most dynamically developing area, the one that could reach the highest level of industrialisation, was Budapest (Pest–Buda) and its surroundings. The city was also the country’s public administrative and political centre, which is why the emerging road and railway network was Budapest-centric. Accordingly the road and railway network has a radial structure with Budapest in the centre, and the region has retained its pre-eminent role in the domestic and international traffic. The basic features of the present road and railway network structure have not changed since the last third of the 19th century (Figure 10.1).

After the fall of Communism Hungary was lagging behind Western European states regarding traffic in motorway networks, in quality and services of existing main roads, but even more in terms of the secondary road network. After Hungary’s accession into the European Union (2004) the available EU funds enabled construction of main elements of motorway network with European importance, building major main roads for 11.5 ton capacity, and certain by-pass roads and reconstruction of railway tracks. These projects could ensure most of the funds for developing the Hun-garian road infrastructure.

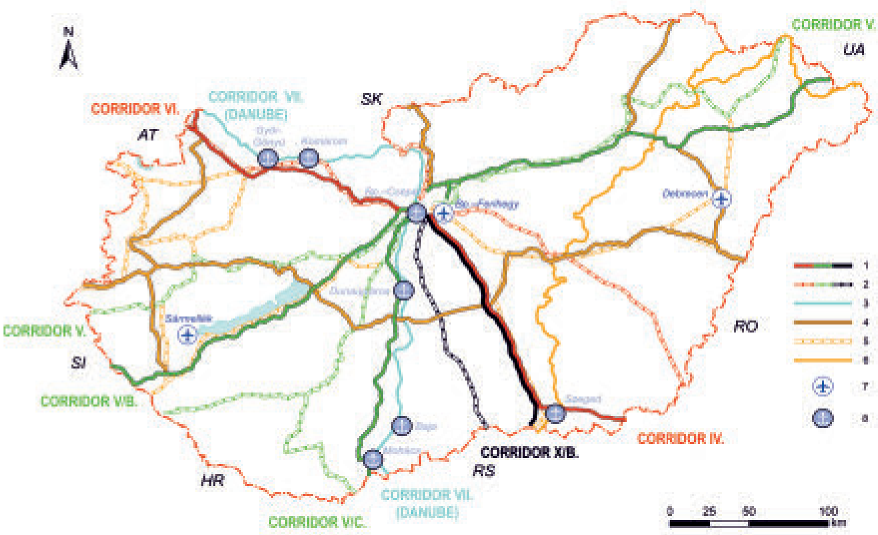


Figure 10.1. Network elements of Helsinki corridors and the European Union Trans-European Traffic Network (TEN-T) in Hungary (based on Institute for Transport Sciences Non-profit Ltd 2010)

1. public road, 2. railway, 3. waterways. *Elements of TEN network:* 4. public road, 5. railway, 6. waterways, 7. airport, 8. port/jetty

Despite major road developments in the past years the infrastructural elements with European importance is still incomplete, even though we could significantly reduce the gap in this field. Extensive development of the motorway network as well as re-construction of the main road net-work, including expansion of several sections of the main roads to 2×2 traffic lanes had to be highlighted. Unfortunately, the other (i.e., those without European importance) traffic facilities could not be improved due to shortage of funds.

The road, railway and waterway concepts of the so-called „Helsinki corridors” defined the planned ele-ments of Hungary’s European

network, and the European Union's Trans-European Traffic Network (TEN-T) expanded them with new elements set out in the Accession Agreement in 2004, when Hungary joined the EU. The TEN-T network was revised in 2011, but its elements relevant to Hungary changed only to minor extent.

Hungary enjoys a favourable position as regards its traffic geography, as several Helsinki corridors cross its territory. Corridor IV is the most important development axis of the country, and the south-west–north-east corridor V, as well as the Danube, as corridor VII join this axis (Figure 10.1, SZÁSZI 2008).

Hungary's road network

The country has very important international connections in all transport branches, and they have increasing potential as a result of developments in the motorway network implemented recently (M3–M30–M35, M7–M70, M6–M60, M5–M43). As statistics show, accessibility of major regions has been significantly improved both regarding transit and traffic within the country.

The existing *motorway network* is strongly Budapest-centred, but still there are areas, where the M85, M86, M8, M9, M6, M44, M4, M35, M49, M3, M34 and M30 motorways planned for improving the access to the capital city should be built or completed, as Budapest can be reached within 3 hours from areas next to the national borders (Figure 10.2).

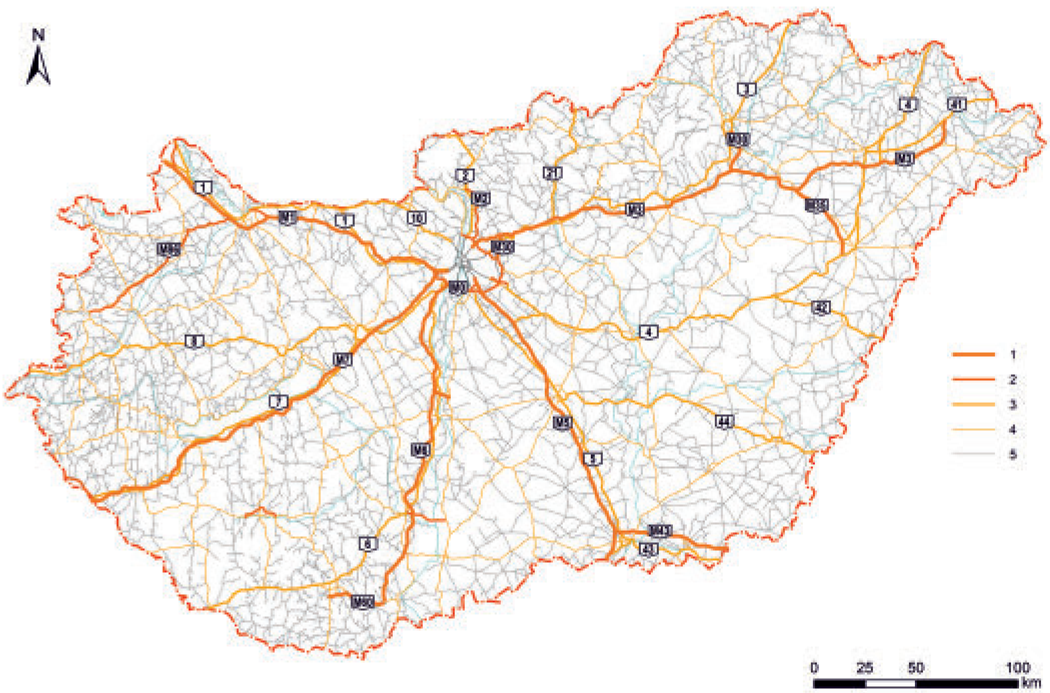


Figure 10.2. Map of Hungary's national road network
1. motorway, 2. highway, 3. main road category I, 4. main road category II, 5. local road

The main road network on a national level is quantitatively satisfactory, but the capacity of roads are often exhausted; there are several sections inside cities where the condition and capacity of bridges calls for modernisation, and the same is true of railway crossings. Over the long term the OTrT — Hungarian National Settlement Equalisation Plan plans large constructions of main road sections, but this programme has not yet started and mostly by pass roads have been built (OTrT 2013).

Access to *small region centres*, which is a critical issue enabling traffic from settlements in small regions to reach basic services and ensuring connection between the settlements, is mainly relevant for the *secondary road network*. In general it may be concluded that building of new secondary roads is not typical, there are places where existing secondary roads are developed, but the length of poor quality secondary roads is significantly higher than the length of repaired roads or roads under repair. Proper operation of this network can be ensured only by improving the quality of the feeder roads.

Despite the above problems we may state that routing and density of Hungary's motorway and main road network (except in the mountains) can ensure that it provides access to almost every concession area — and practically these areas can be always approached.

Hungary's railway network

Act CXCVI of 2011 sets out several categories for railway tracks. The first category includes the *national basic network railway tracks exclusively owned by the state*. Within this the first group contains tracks forming parts of the Trans-

European railway freight network, and the second includes the national basic network railway tracks that do not form parts of the Trans-European railway freight network. The Act lists all relevant railway tracks item-by-item.

The other category of railway tracks is *railway branch* listed in Government Law Decree 194/2016 (VII. 13.), Annex 1, also item-by-item.

The third category contains the railway line operated by GYSEV – Győr–Sopron–Ebenfurt Railway Ccl (Figure 10.3).

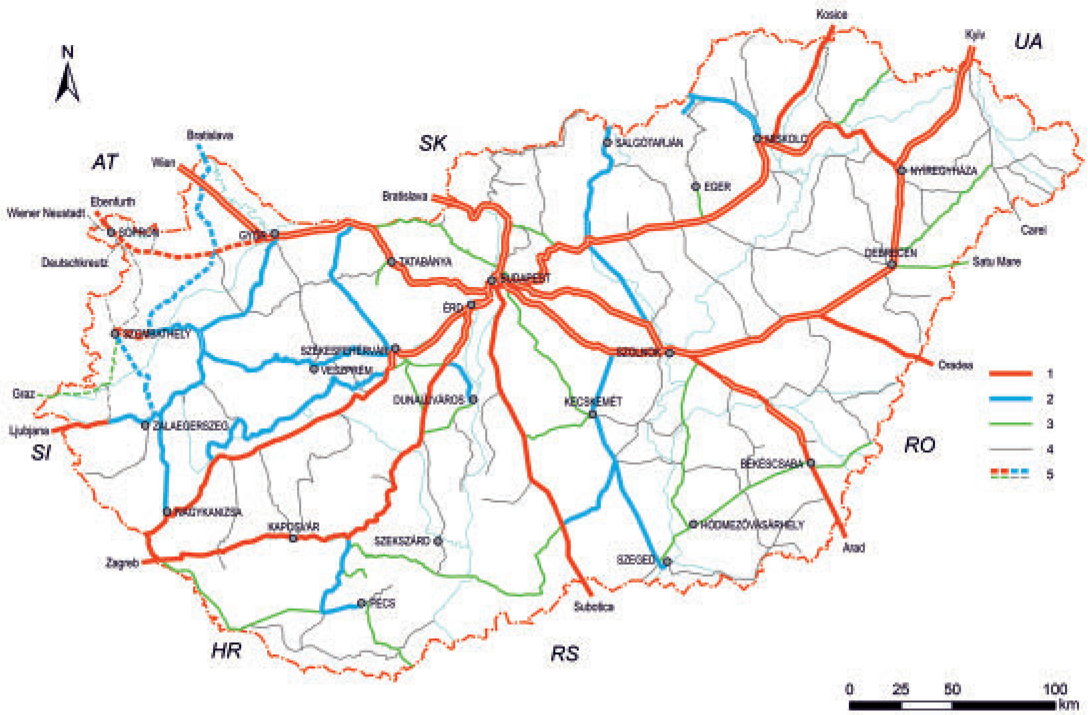


Figure 10.3. Line categories of Hungary's railway system (source: MÁV Hungarian State Railways Ccl)
1. international backbone line, 2. backbone line, 3. other main line, 4. other line, 5. GYSEV line

Passenger transport by railway has been recently significantly declining in the country. Most of this segment was shifted onto road transport, and passenger transport by railway has been continuously losing out. The situation is similar in case of freight transport. Though regarding unit cost this form of onshore transport is the cheapest, trends show a declining curve due to relatively high time demand (including the significant role of double loading, as well as timetable of freight trains), so railway freight traffic has been declining year-by-year. Most part of freight traffic shifted onto road haulage (Komlós 2003; state of the transport sector — KSH 2013).

As a consequence of significant decline in railway traffic, railway lines with low traffic were rationalised in 2009, when some of the economically unprofitable lines were suspended or shut down for good, and some other were eliminated. There were certain lines where only passenger traffic was closed and freight traffic keeps on going. In other cases the total railway traffic was terminated but the railway tracks are maintained, preparing for eventual re-start of traffic, in a few cases, lines were eliminated, and rails and railway structures were removed or destroyed.

In certain lines suspended in 2009, the passenger and freight traffic was later re-introduced. Despite the above-mentioned problems we may state that routing and density of Hungary's railway network (except in the mountains) can ensure that it provides access to almost every concession area — and practically these areas can be always approached (Békési 2015).

Hungary's waterway transport

Regarding waterway transport there are two objective difficulties, in addition to slow speed; the first is the classification of navigable waterways that defines the type of ship, barge, pusher craft, etc. is allowed to move on the given waterway, and it also determines the transport capacity. The other is the existence or lack of appropriate ports. Commodity goods can be transported with and loaded onto and between ships only in appropriately constructed ports equipped with sufficient loading capacity. In Hungary four ports were built on the Danube and one on the Tisza that can meet international loading standards.

Danube is Hungary's international waterway, entering the country at Rajka (1,850 rkm) and leaving her at Mohács, at the south border (1,433 rkm). According to the classification of UN European Economic Committee the Danube section upstream Budapest is a waterway in VI/B class, and downstream Budapest is in VI/C class (Figure 10.4).

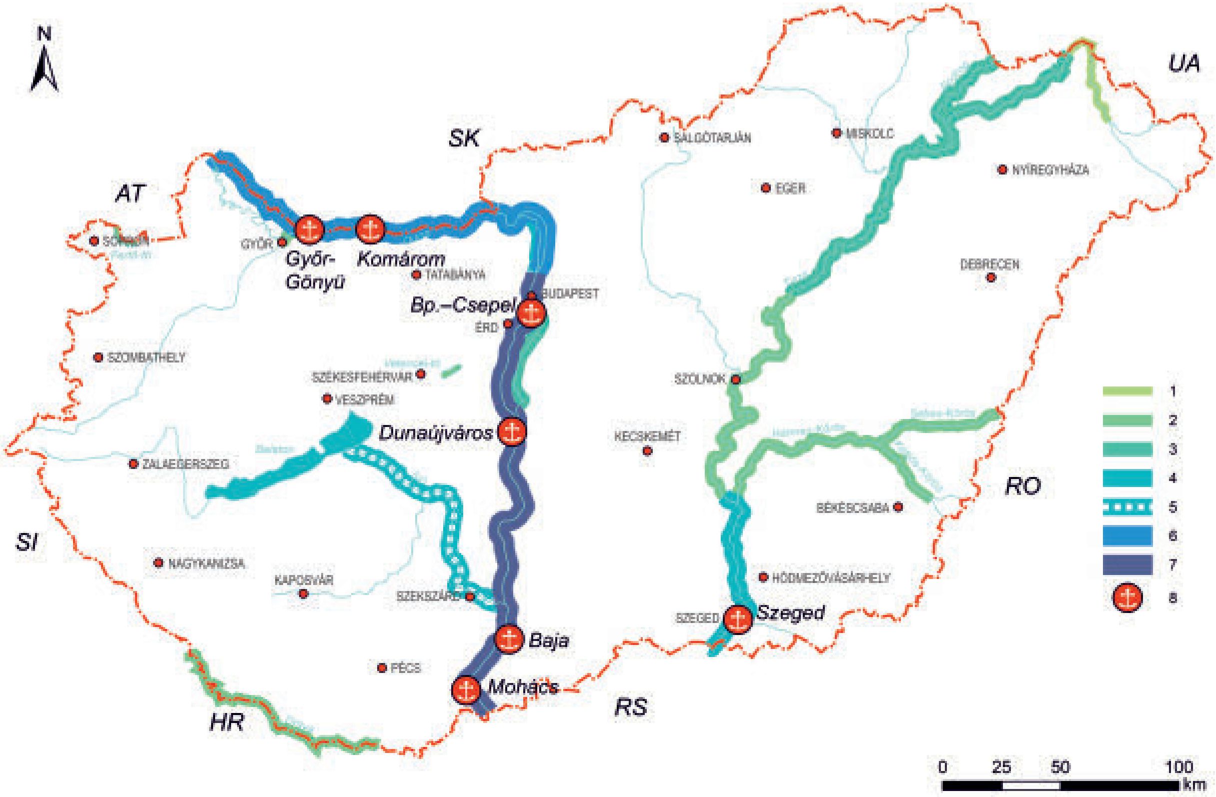


Figure 10.4. Categorisation of waterways in Hungary (source: Institute of Traffic Science Non-profit Ltd 2010)
1. category I, 200 tons load capacity; 2. category II, 500 tons load capacity; 3. category III, 650–1,000 tons load capacity; 4. category IV, 1,000–1,500 tons load capacity; 5. category IV, periodically; 6. category VI/B, 4,000–4,500 tons load capacity; 7. category VI/C, 4,000–6,200 tons load capacity; 8. port

The Danube section between Rajka–Budapest fails to meet the above requirements at several points (primarily in the depth and width of the navigation path). Since the commissioning of the Gabcikovo (Bős) the international waterway has been progressing in the power canal of the barrage and joins the Danube at Szap (1,811 rkm). The Danube (Helsinki corridor No. 7) as waterway forms part of the Danube–Main–Rhein waterway, thus it has outstanding significance.

As specified in the Government Decree 151/2000 (so-called AGN Treaty) on waterways with international significance, waterways classified into category IV or higher include the following: the Danube; the Tisza section between Szeged and the country border; Sió; and Lake Balaton. However, only Danube is classified as an international waterway, by virtue of an international treaty.

The Tisza is our waterway with most important regional significance. This river joins Danube beyond the country's border (at Titel, 1,215 rkm). There is a bilateral navigation treaty enabling Hungarian ships to use this waterway and to reach the Danube through Tisza (and to return). This Tisza section, i.e., between the country border and Szeged, has variable waterway parameters, thus its classification also varies between I–IV.

Reaching the concessions areas through waterways in most cases presents difficulties due to the above mentioned navigation problems and the paucity of suitable ports.

Energy generation and energy transmission

Hungary is poor in primary energy carriers, so most energy carriers required for satisfying the demand are secured from import. Power stations act as the bases of domestic electricity generation, where the primary energy is nuclear energy, natural gas, oil, coal (lignite) and renewable energy.

Power and hydrocarbon (natural gas and oil products) transmission systems with national and international significance were implemented for supplying the generated domestic and imported energy (domestic and international) and its distribution within the country. The entry points of these pipeline networks are international points of delivery, primarily international connections and points of transfer along the border.

Transmission systems were connected to the implemented base networks carrying products (power, natural gas, oil and product) extracted from domestic reservoirs, sources and generating bases. A consistent network system was implemented

for the transmission of energy carriers domestically generated or produced or imported. Naturally these systems are able not only to off-take and transmit the imported products as required but also to export domestic products.

Energy carriers acquired from generation and production are distributed throughout the country with the help of the base network system, ensuring that energy can be supplied to everywhere from this distribution network.

Point 4.m. of the parliament resolution no. 77/2011 (X. 14.) on the National Energy Strategy gave a mandate to the Government *to ensure exploration of domestic mineral resources to be utilised for energy supply and set out conditions for strategic reserve management and for the domestic coal mining sector.*

Security and independence of energy supply is an issue of national security and priority for the energy policy. Hungary's energy supply depends significantly import, and within that there is a unilateral exposure pre-dominantly in case of natural gas. Hungary's annual natural gas consumption is higher than 8 billion cubic metres (BCM) of natural gas. Its significant portion is residential or household consumption.

Hungary's electricity network

The domestic supplying bases of the power network system are the power stations. Paks nuclear power station has a predominant role in the power generation. The points of transfer along the border are the international points of supply. The high-voltage transmission network starts from these points of supply, forming the basic network for the domestic power supply system, where the voltage level is defined by the voltage of power generated at the points of supply or removed at points of delivery. Based on the voltage level of supply the system has 400, 220 kV networks.

There is a 120 kV network starting from the sub-stations of the base network as the backbone of the distribution network. This backbone network ensures supply for the 120/20, 120/10 kV sub-stations and other industrial transformers securing power supply for smaller-greater regions, counties and settlements. Supply is on a county and regional level.

Lines of the backbone network of the domestic power distribution system cover the total country. The lines of the 400/220/120 kV transmission network and the 120 kV distribution network can practically reach every concessions area at very short distance or cross most of the areas. These lines can ensure power supply for the concession areas and in possession of the produced HC minerals can feed the power generated in the local power stations into the national power system (Figure 10.5; ALFÖLDI 2016).

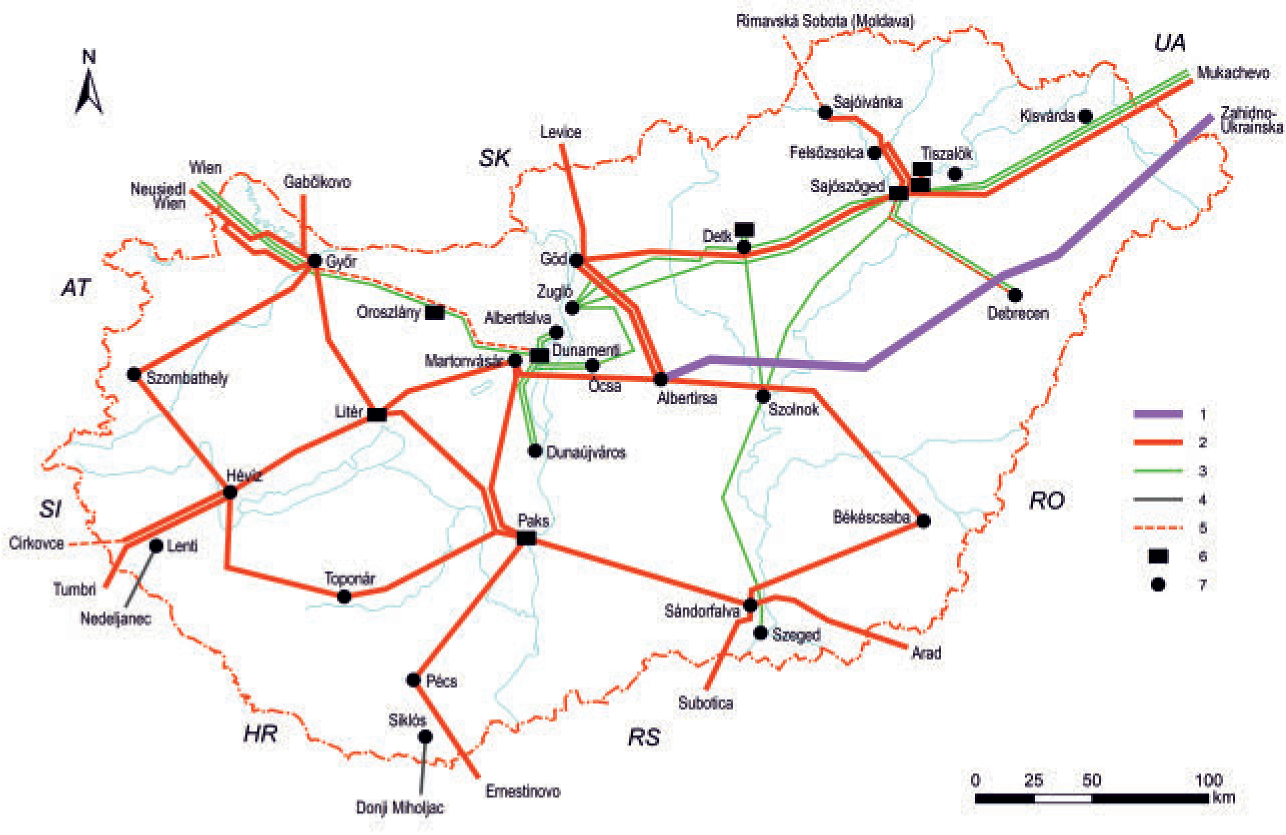


Figure 10.5. Power transmission grid of Hungary in 2011 – With cross-border inter-connections. (source: MAVIR Hungarian Independent Transmission Operator Compani Ltd 2011) 1. 750 kV transmission line, 2. 400 kV transmission line, 3. 220 kV transmission line, 4. 120 kV transmission line, 5. planned line, 6. power plant, 7. node

Natural gas transmission pipelines

Nearly 70% of Hungary's total energy consumption comes from natural gas, and in terms of quantity it is more than 8 BCM/year. Nearly 45% of this quantity, including district heating, is residential consumption. Power generation is at 3 BCM/year. A significant part of Hungary's natural gas demand arrives through one single transmission pipeline (the Barátság [Fraternity] gas pipeline) from Russia, causing an exposure regarding the security of supply. The third point of supply is connected to the Slovakian transit pipeline at Veľké Zlievcé and delivers natural gas to Vecsés junction supplying Budapest and the agglomeration. In addition the network operated by FGSZ Natural Gas Transmission Company Ccl offers the chance for major gas transit to Serbia, Bosnia and Croatia. The Arad–Temesvár natural gas pipeline connects the Romanian Transgas network and the Hungarian gas network, and if the capacity upgrade described in the inter-state agreement is completed, the pipeline will transmit 4 BCM/year natural gas both ways. From 2016 the daily import capacity of the cross-border natural gas import pipelines has been higher than the daily peak demand of consumption.

Hungary's security of gas supply depends on a complex international cooperation based on the existing *Barátság* and the already built and planned cross-border gas pipeline. Substantial natural gas and crude oil import causes a strong exposure in energy supply for the country. Thus, the political goal is to explore and produce the domestic probable hydrocarbon reserves, and thus to reduce import exposure. Exploitation of undiscovered domestic hydrocarbon reserves may facilitate implementing the future domestic energy strategy.

Points of supply of the natural gas supply system are the domestic natural gas reserves and the points of delivery along the border for international imports. The high-pressure (20–64 bar) transmission network starts from domestic and international points of supply and it forms the base network of the domestic natural gas supply. The natural gas transmission networks form a consistent national system, and FGSZ Natural Gas Transmission Company Ccl holds the exclusive ownership and management rights holding the natural gas transmission and system operator license (Figure 10.6).

Transfer stations installed onto the transmission networks supply the pressure reducing stations, from where the high-medium pressure distribution network starts forming the backbone of gas supply for various regions and settlements. This high-medium pressure backbone distribution network supplies the gas transfer stations as the basis of supply for various regions or settlements.

Figure 10.6. High-pressure natural gas transmission network of FGSZ Natural Gas Transmission Company Ccl (source: FGSZ, 2010)

1. gas pipeline with d > 1,000 mm (diameter), 2. gas pipeline with 600 < d < 800 mm, 3. gas pipeline with 300 < d < 600 mm, 4. gas pipeline with d < 300 mm, 5. centre; 6. compressor station, 7. import/export point, 8. entry point from domestic production, 9. injection/withdrawal point of underground storage, 10. gas transfer station, measuring station, 11. backhaul, 12. point of inter-connection (FGSZ-MGT), 13. nod

The medium or low pressure distribution network and the intra-settlement distribution network starts from the gas transfer station and the pressure regulator installed next to the station offering direct supply for consumers. As a result of earlier development programmes, centrally supported, Hungary's pipeline gas supply is almost fully secured for nearly all settlements.

Planned national hydrocarbon transmission pipelines

Volume II of Act XXVI of 2003, the National Development Plan was revised (Basic works, 2013), as a document revised through a reconciliation process, and the following planned high-pressure gas transmission and product pipelines were identified in this document:

Natural gas transmission pipelines
Ercsi–Százhalombatta,
Városföld–Adony–Ercsi,
Ercsi–Győr,
Taksony – Budapest XXI. district.
Product pipelines
Százhalombatta – Rajka (Slovakia).

Points of connections of the producing natural gas fields

Production of gas and crude oil fields prepared for production can begin only if the product can be supplied into the domestic natural gas and crude oil basic network through the so-called points of supply. Figure 10.6 presents the main points of supply for gas fields.

Crude oil and product pipelines

Hungary's crude oil consumption is nearly 6 million tons/year, and this figure has been consolidated during the past decades sector. Oil refineries consume most of the total quantity, while a minor part is used for power generation. The pipeline infrastructure focusing onto supply can take away the heavy load from road and railway transmission. The length of the national and international transit pipelines and oil product and supply pipeline and the line between the refineries and areas of consumption is 848 km (KSH Hungarian Central Statistical Office 2013, Figure 10.7).

The "Barátság" crude oil pipeline is one of the longest oil pipelines in the world, and notable among international transit pipelines. The pipeline was built during the Soviet era to a nearly 4,000 km length, so as to transmit crude oil westward from the Central Russian regions.

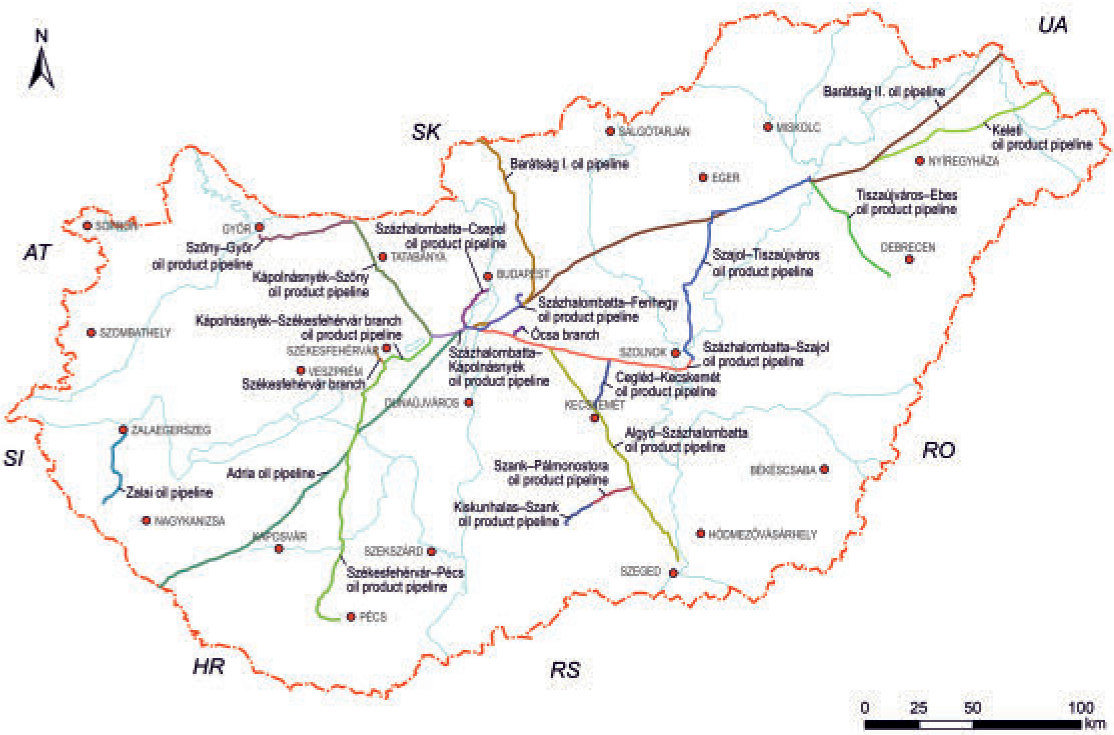


Figure 10.7. Hungary's crude oil transportation network (source: Lechner Lajos Knowledge Center Non-profit Ltd, 2012)

Product pipelines were built between refineries and major consumers. Among them the main lines are Százhalombatta–Csepel, Százhalombatta–Székesfehérvár–Pécs, three Százhalombatta–Szajol–Tiszaújváros product pipelines with 600 kilotons/year capacity, and the product pipeline importing chemical feedstock from Russian and Ukrainian sources (fuel oil with sulphur content higher than specified for domestic standards).

The scope of distillation products transported by product pipeline has also been significantly enlarged. In addition to gasoline and fuel oil lines there are two ethylene pipelines in operation (Tiszaújváros–Kazincbarcika and Tiszaújváros–Kalush [UA]). Along with distillation products, liquid ammonia and oxygen pipelines also operate applying safe technology in line with specific needs of the given product.

Points of supply of oil and product transmission systems are partly the domestic places of discovery and production and points of transfer from international import installed along the border. The hydrocarbon (crude oil and distillation products) transmission network starting from domestic and international points of supply forms the domestic supply system. Oil and product transmission networks form a system of international and national significance. Transfer stations installed on the transmission networks provide supply for special-purpose pipelines (built as branches) that ensure direct supply for consumers.

Licensing process for natural gas and crude oil transmission-pipelines

Building the licensing mechanism for gas and crude oil transmission pipelines, required for energy security, is a complex multi-step process. A *preliminary environmental impact study* (PEIS) must be performed as the basis for the competent authority to define the requirements for the IPPC (Integrated Pollution Prevention and Control) in conformity with PEIS results, and an IPPC can be issued following the PEIS document and the eventual environmental impact study.

Preliminary analysis process

In the case of activities defined in Government Decree 314/2005 (XII. 25.) the environment user should initiate a preliminary analysis at the competent authority. As the Annex 1 of the Decree classifies the pipeline transmitting *gas, crude oil, oil products, chemicals or carbon dioxide planned for geological storage (including the pressure booster units) as* "Transmission, storage" as activity no. 41, thus the referred Decree classifies the implementation of such pipelines as activity subject to an e*nvironmental impact study*.

Pursuant to Point 77 of Annex 3, in case the power, gas, steam, or water supply activity is using higher than 40 bar operating pressure, then the implementation of the planned natural gas distribution pipeline is classified as activity subject to an *environmental impact study* subject to the decision of the *environmental protection authority adopted in the preliminary analysis.*

As specified in the above referred laws, a *preliminary analysis documentation* should be submitted to the competent authority for the performance of such preliminary analysis.

The purpose of this preliminary analysis is to decide if the given activity will have an effect on the environment that can justify the need for performing a *detailed environmental impact study*, and IPPC.

Preliminary analysis documentation

Prior to starting a preliminary analysis, the party performing the activity should prepare a *preliminary analysis documentation*, the contents of which are defined in Annex 4 of Decree 314/2005 (XII. 25.).

The preliminary analysis process starts when the preliminary analysis documentation is submitted to the competent authority. After the preliminary analysis process starts, the competent authority issues a publication about launching the process, and sends it also to the notary of the affected settlement and the submitted documentation in order that the potentially affected community can also be informed about the new process and can offer comments on the planned activity and its impacts. The acting competent authority involves also the other affected competent authorities into the process, and makes arrangements for holding a public hearing, if required.

Results of preliminary analysis

As the final action to close the preliminary analysis, the competent authority adopts a resolution based on the submitted preliminary analysis documentation, findings of its own and other competent authorities and comments offered by the affected parties. In this resolution:

— it concludes based on results of the preliminary analysis whether the implementation of the planned activity may lead to significant environmental impacts, as well as

— in case any significant environmental impact is assumed, it defines the requirements for the *environmental impact study*.

— if no significant environmental impact is assumed, and the activity is not subject to Annex 2, it provides information about the other permits required for starting the activity;

— if the preliminary analysis documentation contained various options, it identifies the option(s) that may allow the implementation under appropriate conditions;

— if during the preliminary analysis any reason emerges excluding the permit for the activity, then this is recorded and it decides that the given activity cannot be permitted,

— in case of significant environmental impact at the Natura 2000 area, criteria for an environmental impact study are set out in compliance with the rules on mandatory content of Natura 2000 area documentation.

The IPPC may be applied for within two years following the day when the resolution becomes final and binding, and this deadline may be extended only once with a maximum extension of one year.

Content of preliminary analysis documentation

Requirements of the content of the preliminary analysis documentation, briefly:

— purpose of the planned activity,

— the basic data of the planned activity and its other options (activity volume, place and area required for the activity, method defined in the settlement documents, required facilities, description of planned technology, place of installation, its delineation on the map, etc.),

— presentation of correlations of the considered options with the area or settlement and development plans, and concepts for utilisation or protection of natural resources,

— for line-bound facility, description of the planned routing and long-term development,

— environmental load of the considered options and preliminary estimate of such load for each phase of the activity,

— preliminary estimate of potential environmental impacts.

Other requirements:

— identification data of the applicant,

— classified data or business secrets that should be separately attached to the documentation,

— possibility for occurrence of cross-border environmental impacts.

Environmental protection and IPPC permits

For activities causing significant load onto the environment or with potential significant pollution to the environment, a permit is required from the competent environmental protection and nature conservation authority. The type of the permit depends on the nature and capacity of the relevant activity, and the potential environmental impacts. Based on the performed environmental impact study and/or the IPPC permit process, the competent authority may

— issue an environmental permit, or

— issue an IPPC permit for the activity.

The authority issues the permits for a specified phase or period which cannot be less than five years. When the permits expire and in case of IPPC permits requirements and prescriptions defined in the permit should be revised in every five years.

Performance of the environmental impact study process in conformity with the *environmental impact study* (EIS) is a pre-condition for issuing an environmental permit.

Local opportunities for economic and community utilisation of hydrocarbon wells

ANDRÁS HERCZEG, SÁNDOR TISZAVÁRI, ZSUZSANNA HERCZEG, ANDRÁS HERCZEG JR

General introduction

Hydrocarbons in nature are complex systems and their state is defined by their composition, pressure and temperature (GARAGULY et al. 2017). There are solid, liquid and gas hydrocarbons at standard conditions (atmospheric pressure and temperature 20 °C).

The following concepts should be explained in order that volume of initial reserve in-place can be understood, as these concepts are applied in sample projects described later:

Based on categories of mineral resources (gas resources) we can differentiate (see: Act XLVIII. of 1993, the Mining Law, 49. § [4]):

Mineral resource: total quantity of minerals supported by exploration data, defined by cut off typical for the given minerals — without applying any technical and economic limits.

Recoverable mineral resource: part of initial mineral resource in-place of a mining plot deducted with resources held in the pillars (boundary pillar, barrier pillar) which is recoverable at the level of the prevailing scientific–technical development.

Recoverable resource: part of the petroleum initially in-place that is at the given time commercially recoverable.

(SPE/WPC Petroleum Reserves Definitions 2001: Reserve: Those quantities of petroleum which are anticipated to be commercially recovered from known accumulations from a given date forward.) In this chapter the quantity of recoverable resource will be analysed and commercially calculated based on the fact of whether local utilisation of the given reservoir, field, gas well can be profitably implemented or not.

Gas technology

Regarding local utilisation it must be mentioned that natural gas extracted from gas wells is not suitable for supplying it to the consumer (SOMFAI et al. 1992). First some components should be separated from the extracted natural gas, namely those that can be used later or have negative effects onto the combustion technology process.

The raw natural gas shall be separated prior to its treatment at the gas technology from water and condensate present in the gas in liquid state. This operation starts with a separator.

Gas technology process is the series of operations enabling the end-consumer to safely and profitably use the raw gas produced from the gas well (Figure 11.1).

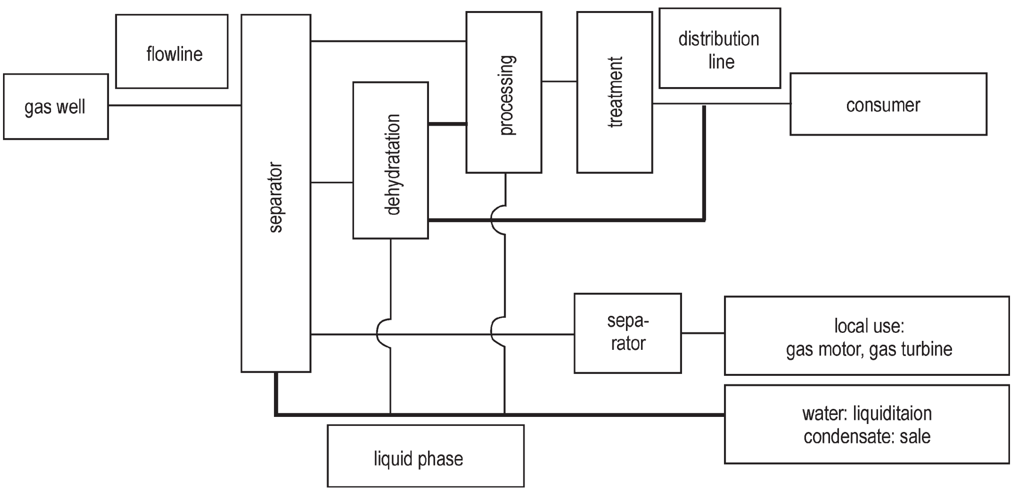


Figure 11.1. Way of the gas from production to the consumer

Natural gas technology process has the following main activities:

— dehydration,
— treatment,
— processing,
— other processes.

Definition of these processes (VIDA 1991):

Natural gas dehydration process: vapour content of natural gas is reduced.

Natural gas-treatment processes: natural gas with the prescribed hydrocarbon and water dew point (usually the same as the dew point) is gained from the raw gas flow.

Natural gas processing: technology for obtaining gas with pure component — or more components in higher ratio, to achieve the demanded quality.

Other processes: gas treatment methods to remove various pollutants or impurities from the gas – CO_2, H_2S, N_2 mercaptans.

Natural gas technology processes are usually based on the following principles (SZILAS 1977):

1) absorption: absorption of gases and vapours in fluids or solid bodies,
2) adsorption: adsorption of gases or liquids on solid bodies or on surface of a liquid,
3) condensations: fluidisation of vapours due to cooling or pressure build-up.

Possible processes of natural gas procession

During *natural gas dehydration* the water and water vapour content of gas is removed. Formation of hydrates and plugs, freezing, icing and corrosion can be prevented by dehydration.

The following processes belong to the group of natural gas dehydration:

1) absorption: with glycol (e.g. glycol),
2) adsorption: with solid bed (e.g. silica gel),
3) condensations: with cooling (e.g. with air, water, expansion, automated).

The key criteria for selecting the proper dehydration process are target dew point and the possible dew point reduction. Cost factor of the above processes might be significantly different.

Setting the hydrocarbon and water dew point simultaneously can be performed by the following processes:

1) condensations: cold separations,
2) adsorption: with solid bed,
3) absorption: combined.

Following processes were developed to extract the key components in gas processing.

1) absorption: (flushing) hot oil, cold oil,
2) adsorption: solid bed, long cycle,
3) condensations: deep cooling or cryogenic.

Process selection depends on the type and concentration of the compounds to be extracted, the amount of gas to be treated, its pressure and temperature, the capital and operating cost of the technology, and the requirements related to the waste gas.

Other CO_2, H_2S and N_2 recovery processes can be classified into the following groups (TIHANYI, CSETE 2012):

— chemical solvents,
— physical solvents,
— oxidations, reduction,
— adsorption,
— cryogenic.

Quality and quantity of the pollutant, volume, pressure and temperature of the gas to be treated, regulations on waste gas treatment, cost of the project and operation should be known for selecting the method.

Liquidation and utilisation possibilities of the liquid phase produced during the gas technology processes should be addressed. Liquid phase may include water and crude oil and condensate.

The produced water may be disposed by injecting it under the surface. The produced condensate is marketable. During gas treatment the separated condensate should be stabilised prior to further operations. Then it can be gathered with the condensates produced during the dehydration process, but a proper storage capacity will be required. If the appropriate condensate quantity is collected, it can be shipped on road using ADR-grade vehicles. A proper filling station should be built for the transport. The produced condensate is not an excise product.

Dehydration and several treatment processes are the most important components of the natural gas treatment process.

Among the above enlisted gas dehydration, gas treatment, gas processing and other processes sample projects in details are presented, those are technically justified based on the relevant geographic locations, quality of the produced raw natural gas and the processed natural gas can be profitably utilised.

Setting the dew point for natural gas water and hydrocarbon

Within gas technological processes the natural gas dehydration can basically define the subsequent gas treatment processes, as in certain cases no gas treatment and gas processing is required after efficient dehydration.

As they are significant, descriptions and flowcharts of gas dehydration processes will be presented in details in this chapter. To help better understanding, Figure 11. 2 processes introduce the basic concepts and terms under the title "Descriptions and flowcharts of glycol absorption process".

Regarding the dew point achievable during the gas dehydration the following processes are differentiated:

— +20 °C or higher dew point can be achieved using air or water cooling (condensations process),

— –20 °C dew point can be achieved using glycol (absorption process), expansion or automated cooling (condensations process),

— –50 °C dew point can be achieved using silica gel (adsorption process).

Descriptions and flowchart of glycol absorption process

Gas absorption is the operation where the gas mixture contacts with the absorbent in order that the water vapour and the condensate components in the gas mixture can be dissolved and the relevant solvent is produced in the absorbent.

The material absorbed in the absorption process does not enter into a chemical reaction with the absorbent, thus the absorbent gained from desorption can be re-used in process.

Dehydration process using glycol is the most widely used method both in Hungary and worldwide. Figure 11.2 presents the dehydration technology process using glycol (Vida et al. 1991.)

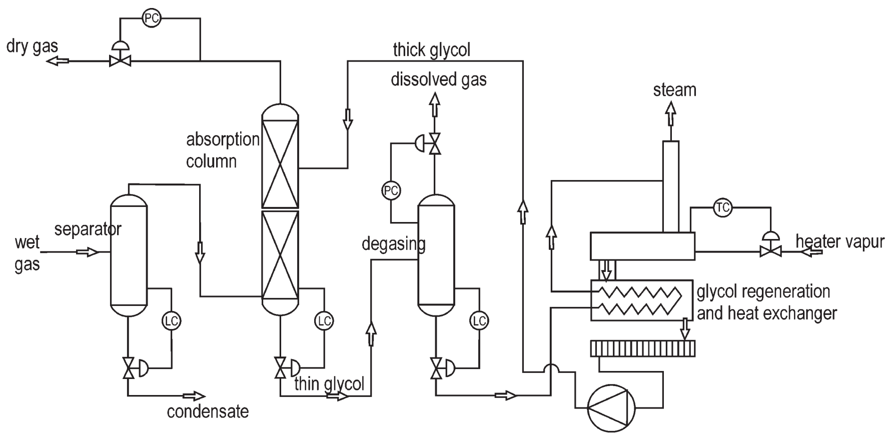


Figure 11.2. Technology flowchart of gas dehydration process using glycol
LC = liquid level control, PC: pressure control, TC = temperature control, FQ = flow quantity

The process contains the separation of the produced natural gas water and its condensate content in the pre-separator. The most important equipment of the process is the absorption column, where the natural gas and the fluid glycol counter-flow meet. Plates and bumpers installed into the flow improve the efficiency of the absorption, and they help the gas and liquid to meet at larger surface.

The diluted glycol is regenerated in a closed system after it crosses the gasification separator by heating.

Dry gas leaving the absorption column can be supplied to the consumer or fed into the gas treatment process.

Glycerine is rarely used instead of glycol, but it is significantly more expensive for absorption processes.

Description and flowchart of silica gel adsorption process

Gas adsorption is a process when the gas mixture contacts with solid, porous material with large specific surface and water vapour and condensate bondage happens.

The material absorbed during adsorption does not involved in chemical reaction with the absorbent, thus the absorbent can be recovered through regeneration and re-used in closed cycle in the process.

Solid adsorbents may include bauxite, aluminium-oxide-gel, silica gel, molecule filters (natural or artificial calcium sodium silicates).

The most often used solid bed gas dehydration unit is implemented with three dehydration columns, and Figure 11.3. presents it this unit (Vida et al. 1991).

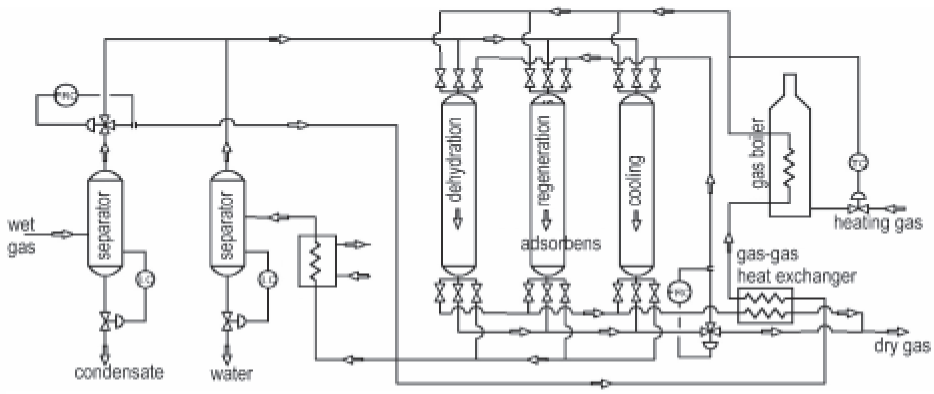


Figure 11.3. Flowchart of solid bed gas dehydration technology (three adsorbents, hot regeneration, long cycle)
LC = level control, PRC = pressure control, TC = temperature control

The process contains separation of the produced natural gas water and its condensate content in the pre-separator. Gas dehydration process takes place in three dehydration columns, operating simultaneously in different operating functions: dehydration, regeneration, cooling. The gas flows in the same direction top-bottom through the columns. Dual-column short cycle time equipment can be more efficient for dehydration of smaller gas flows as it needs shorter reaction time.

Dry gas is used for regenerating the solid adsorbent, which absorbs the water vapour and the condensate from the adsorbent. The absorbed liquid is separated by heating the regeneration gas leaving the adsorbent. The hot regeneration and cooling gas should be cooled back in order that it can be re-supplied into the main gas flow of the dehydration line.

Continuous and gradual deterioration of the quality of adsorbent is a typical and important operating problem of solid bed equipment.

Cold separation gas treatment process with automated cooling

Natural gas-treatment should set the water and hydrocarbon dew points up to 0 – –20 °C.

The basis of condensation process is that due to cooling (gas–gas heat exchanger and automated cooling) the water vapour and some hydrocarbon components are condensed and thus it can be separated from the gas (Figure 11.4; VIDA et al. 1991).

The process contains the separation of the water and condensate content of the produced natural gas in a pre-separator.

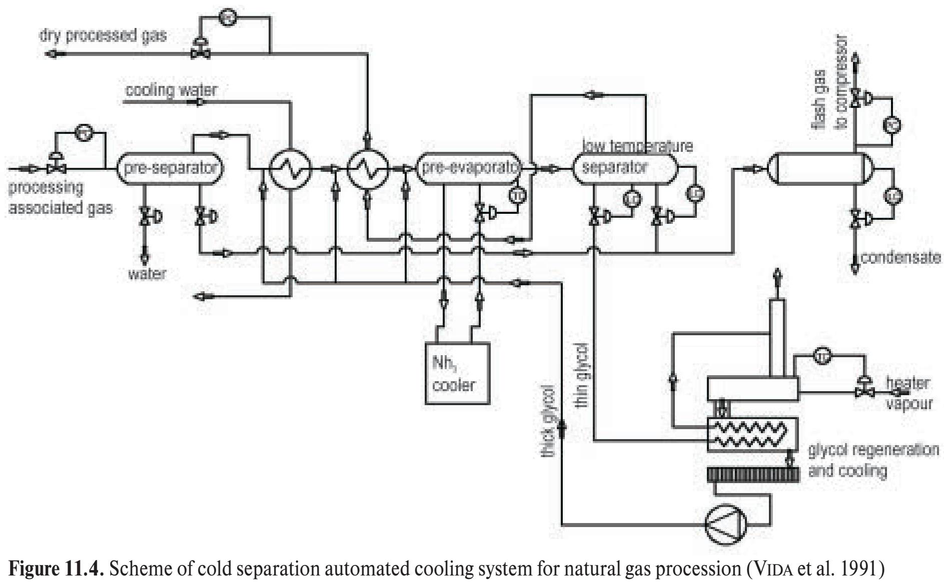


Figure 11.4. Scheme of cold separation automated cooling system for natural gas procession (VIDA et al. 1991)
LC = level control, PC = pressure control, TC = temperature control

Next technology operation is water and gas cooling after the pre-separation. Gas is cooled to +10–0 °C and thus the further liquid phase is separated. Then using the expansions valve the gas temperature can be further reduced.

Separators perform one of the most important operations of the technology, when liquid formations produced by the cooling are recovered. The treated dry gas and liquid phase leave the separators.

It is important to note that during the cold separation natural gas treatment technological process inhibitor should be applied in order to prevent hydrate formation. The inhibitor can be re-used after re-concentration.

Ways of utilisation

Ways of utilisation need to be analysed to select the processes that enable development of smaller gas fields with inert gas content (henceforward: inert gas). The key factor for determining the value of the gas in a reservoir is the cost required for natural gas production and dehydration, treatment, purification, and the cost of projects prior to utilisation, the expected profit and amortisation/depreciation.

When utilisation is analysed the following factors are considered. In addition to the reserve size, production maximum on the field and the optimum production profile are analysed. It should be also analysed if so-called if local utilisation makes it possible flat production and its time span is planned. If seasonal production does not fit for gas reservoir, continuous deliver should be planned. Various utilisation possibilities are presented in this chapter including the key technical conditions that need to be taken into account when a specific field is selected. Theories developed by Szilas (1975) and Pápay (1972) were used for the analysis of the relevant transmission/logistic processes.

Utilisation with gas motor or micro gas turbine

Gas motors (Figure 11.5) are the least sensitive to gas composition, thus gas motor is applied in biogas power stations. The other benefit is that they can be easily installed almost every-where. Their space demand is low, and using adequate noise dampeners, noise emission can be minimised. Their disadvantage is high maintenance cost. The inert gas can be utilised also with special-purpose micro gas turbine. Micro gas turbines have advantages of efficiently coping with higher inert content (as low as 35% methane content could be sufficient), low maintenance cost, low noise load and smaller space demand than for gas motor. The disadvantage is that it generates power with lower efficiency than gas motors do, somewhat higher project cost, and it is less efficient in managing eventual volatilities in gas quality.

Figure 11.5. Ener-core gas turbine (www.ener-core.com)

In case of gas motors two energy products are generated power and so called waste heat.

If the produced waste heat is utilised that is the most efficient way to apply gas motor or micro gas turbine. The waste heat is used in gas dehydration and treatment processes or sold for target consumer.

A similar process can be identified in case of biogas power stations. Unfortunately, when domestic biogas power stations were implemented, heat utilisation was ignored in most cases. Only 1-2 power station projects could have been paid back without a state subsidy system (so-called KÁT, mandatory off-take) even despite state subsidies granted for the projects.

In addition to waste heat utilisation, installing the unit next to an electricity consuming plant is a good idea. The rationale is that if a gas motor generates power only for the electricity network, then the sales price of this power is 13–18 HUF/kWh. A consumer with high power demand can purchase the power under an individual contract for 24–35 HUF/kWh from a

distributor. It is obvious that it is better for both the power generator and the consumer to maintain a direct sale and purchase structure between them, because if the generator sets a 21–24 HUF/kWh price, this is still a better option for the consumer and buy directly from the generator. Naturally, the best solution is to implement the project upfront involving a consumer in a consortium.

It must be noted that waste heat can be very often utilised only seasonally, thus an air cooling system or absorption cooling system is needed for dissipating the generated thermal energy, mainly in summer. Manufacturers usually include this system into plans for gas motor or gas turbine installation. Gas consumption will not dramatically change, but in most cases only power sales can be calculated as revenue.

Agriculture, i.e. a farm with hydroculture greenhouse system is a good example for utilisation. The power is required throughout the year (for cooling houses, cutters, separators, process and packaging units); in winter greenhouse heating needs huge quantity of thermal energy. The generated power can be utilised for recovering further thermal energy through heat pump units adjusted to gas motor, and it can supply dehydration and distillation units, etc. As gas motors are the least sensitive to gas composition, gas treatment cost can be reduced moreover; in some cases even gas treatment can be skipped. If applying micro gas turbine a more serious treatment is needed than for a gas motor.

Companies manufacturing motors operable with inert gas: Deutz, Perkins, Waukesha, Jenbacher, Caterpillar.

Companies manufacturing micro gas turbines operating also with inert: Capston Turbine, Turbec (T100) Microturbine, Ener-Core. Companies manufacturing gas motor or micro gas turbine need mainly the following parameters for preparing a bid proposal:

— Wobbe number: the third combustion parameter for the fuel in addition to gross and net calorific value. This is calculated by dividing the gas calorific value with the square of the gas relative density. The thermal energy generated during the process is pro rata with the Wobbe number.

— Methane number: a metrics for measuring the anti-knock capacity. The inert content has basically no negative effect, but gases with higher hydrogen content do (e.g. propane).

— Inert content: to define the exact quality parameters we need to know the exact inert content: CO_2, N_2, H_2S

After selecting the gas-firing gas motor or gas turbine the manufacturer will specify the parameters for treatment, such parameters are the water and hydrocarbon dew points. The required dew points are set during the treatment by separating the liquid at given temperature.

To adjust gas motor or micro gas turbine a field with minimum 3 Mm^3 or higher recoverable resource is required. The following project types can be recommended for gas motor or gas turbine consumption:

Utilisation in gas boiler

Gas should be treated for utilisation in gas boiler, but project cost of boiler is the lowest. As gas consumption is continuous, connection should be established with consumer centres that permanently need thermal energy. E.g. when permanent hot water demand is supplied in a district heating system. Manufacturing may need permanent thermal energy, like pharmaceutical, chemical, glass, waste processing plants, fertiliser production, ethanol, bio-diesel, vegetable oil production, etc.

Wobbe number is the best characteristic feature when gas is used in boiler. Installing or manufacturing a gas boiler special care is needed. It needs to ensure that the flashpoint of the inert gas and air mixture should be in limits, and quantity of components causing corrosion do not exceed upper limit.

Utilising gas with inert content, boilers with large water space are traditionally applied, but there are several manufacturers offering individual solutions based on precise information on composition of gas.

Extremely corrosive components like hydrogen sulphide and aromatic compounds should be separated during the treatment to ensure safe operation for the boiler. Cost of manufacturing and maintenance boilers which use gas un-treated gas is high due to corrosion-resistant structural materials. Aromatic compounds can be easily separated using e.g. propane cooling line. Hydrogen sulphide can be recovered with adsorption separation using activated carbon charge.

When hydrogen sulphide is separated with adsorption, a gas flows through a tank filled with solid charges with activated carbon. Hydrogen sulphide content may drop below 1 pap during this process. There is no reclamation of adsorbent on the spot, so when it is saturated it needs to be changed.

Gas boilers can be applied when gas production is over 50 m^3/h.

Partial of natural gas partial purification, supply to target consumer

One of the most efficient utilisation methods from technical and economic aspects, when contract is concluded with a consumer with high natural gas demand. Such consumers are f.e. brick plants, glass factories, chemical plants, etc. Some cases plant technology can be properly operated by gas that no fulfils gas grid standards.

The required gas quality of the plant is defined by energy engineers. Gas with inert content needs purifying to meet demanded gas quality. If the inert component is carbon dioxide, so a separation technology should be built into the gas purification system.

If the consumer has heat utilisation unit there is no need to build it into the purification system. However, a carbon dioxide separation technology is required, and a natural gas pipeline should be also built to reach the target consumer (planned 6 bar pressure pipeline is sufficient).

There are several methods to separate carbon dioxide water scrubbing technology, absorption separation with amine, VPSA adsorption separation, TSA adsorption separation, membrane technology, etc. As the said technologies can be important they are described next.

High-pressure water or organic scrubbing

High-pressure water scrubbing is one of the most widely applied method for biogas treatment, but also used in several areas connected to inert gas. During this process the compressed gas containing CO_2 (~8 bar) flows through a counter current "water column" (absorption column). Figure 11.6 presents the equipment. During water scrubbing the water can much better dissolve CO_2 than methane. It can remove most of the hydrogen sulphide, but some methane too. The liquid is regenerated in a separate tank (desorption column) by rapid pressure drop, when carbon dioxide and the other dissolved components are removed by the air in the counter current. Oxygen and nitrogen remains in the gas during the next circle, thus this process is not applicable to reach very high methane content.

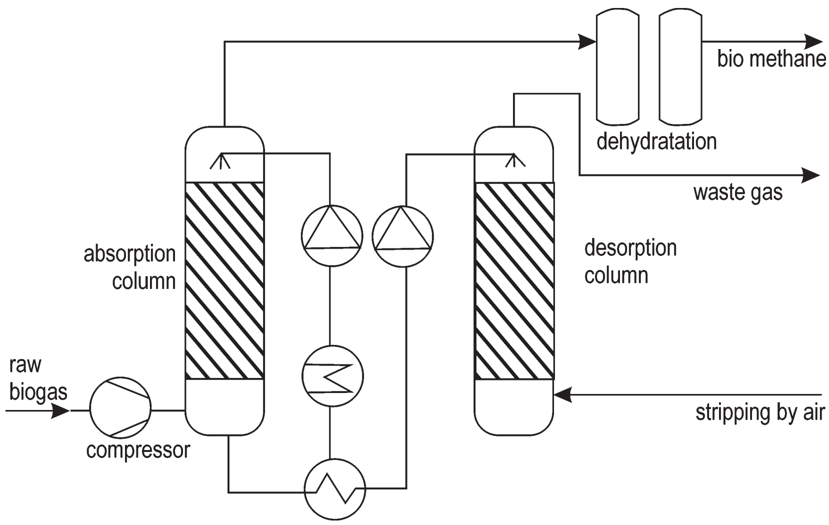


Figure 11.6. High-pressure water scrubbing

Organic solvent, e.g. polyethylene glycol can be also used as absorbent instead of water. In this material carbon dioxide can be better dissolved than in water, so the biogas can be purified with smaller equipment and less solvent. This method is absolutely excluded if we want to breed algae from the separated CO_2. Disadvantages presented for water scrubbing are relevant here as well.

In summary: physical absorption is not a good solution for biogas treatment, because too much solvent is needed for reaching 1-2% CO_2-level, moreover oxygen and nitrogen is also entering into bio methane, and a minimum volume of methane is emitted into the environment.

Amine scrubbing

To purify inert gas with carbon dioxide content chemical absorption process that is amine scrubbing is applied. In case of high volume flow (8,000–20,000 m^3/h) only this technology is cost efficient, but membrane technology methods gather ground. Similarly to water scrubber, amine is fed to the top of the scrubbing column in a counter current, which first physically dissolves, then chemically bind the carbon dioxide. Amin (mainly: MEA, DEA, MDEA: methyl-diethanolamin) can much better dissolve carbon dioxide than water or organic solvents thanks to close chemical relation of amine and carbon dioxide. Regeneration of chemical scrubbing liquids is more difficult than other solvents; the scrubbing liquid should reach 160 °C temperature. CO_2 leaves scrubbing liquids on that temperature and generally waste heat (e.g. from compressors) is used for this. By the end of the process gas contains at least 98–99% methane. This method can be used for treating gas to deliver into pipeline. The major disadvantage of this technology is that during regeneration some of the scrubber liquid evaporates and it must be refill amine is extremely polluting to the

environment and it is a toxic compound, so it is reasonable to replace this technology with an environment friendly one in the future.

VPSA (Vacuum Pressure Swing Adsorption) method

VPSA method utilises that some gas components can be bound to solid surface. Figure 11.7. presents the equipment. Generally activated carbon and molecule filters are used for fixation carbon dioxide. The gas with high carbon dioxide content flows through the adsorber tank at high pressure. Typically 4 or more tanks are used. The adsorber binds most of the carbon dioxide and also some methane.

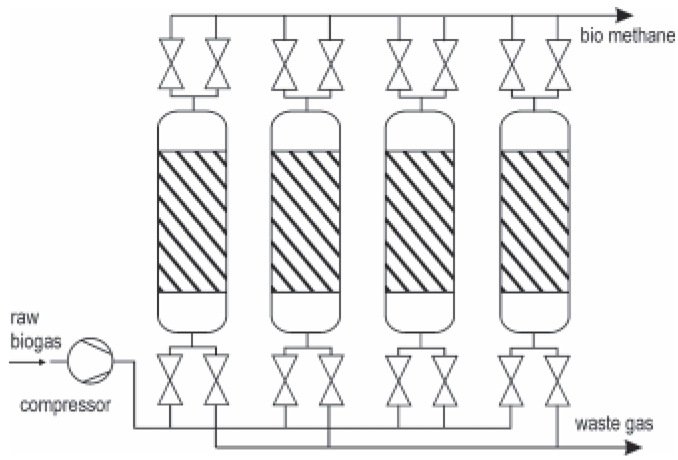


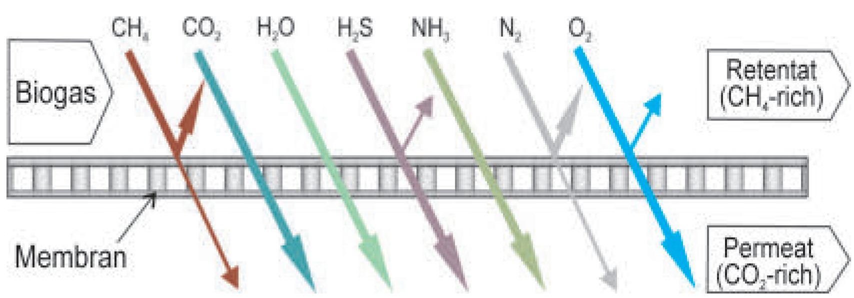
Figure 11.7. Flowchart of pressure swing adsorption

After saturation the adsorber is regenerated through gradual pressure drop. Regeneration first step when saturated adsorbent tank is connected to a tank containing a charge already regenerated. Pressure of the charge to be regenerated is boosted up, while the pressure of the saturated is reduced. Second step when the pressure is decreased to atmospheric pressure and the total bound methane and some of the carbon dioxide is separated from the adsorber. This gas mixture is re-purified with re-circulation to avoid loss of methane. During the third step a near-vacuum pressure is secured in the tank. Carbon dioxide is separated from the adsorbent and is removed from the tank. The fourth step when the pressure is again boosted to bring the adsorbent in operating condition. It is important to note that this technology can be used if hydrogen sulphide and water vapour is removed previously. This technology can ensure very high (even 99%) methane concentration with no environment pollution. However, the technology can be very costly in case of lots of gas.

Membrane technology

When using membrane technology for gas separation the carbon dioxide leaves the permeate, while methane remains in the retentate (Figure 11.8). The materials of the used membrane is permeable for the carbon dioxide but not for the methane. The rate of separation can be enhanced by increasing the inlet pressure, and reducing the pressure on the permeate side with a vacuum pump. If filtering is not perfect, further membrane separation is needed on the permeate and retentate sides, thus a multi-step equipment are implemented.

If gas production is less than the demand, then gas with inert can be mixed up with pipeline gas or gas taken from the distribution system. Mixed gas will have lower inert content and the produced inert gas needs less purification.



11.8. ábra. Membrános technológiával történő szűrés (www.nachhaltigwirtschaften.at)

Under favourable conditions it is adequate to mix inert and natural gas and there is no need to apply separation technology.

In certain cases the inert component is not only carbon dioxide but nitrogen too.

Nitrogen can be separated using the above presented membrane technology or cryogenic process.

Cryogenic process can be a two-step or three-step method, subject to the technology.

During a cryogenic process the gas is cooled down to –150 and –165 °C temperature in several steps. In the first step a turbo expander cooling circle operating with nitrogen medium is applied, where the inlet gas temperature drops below –150 °C. In the subsequent steps the gas pressure and temperature is reduced with the help of expansion valve. Every expansion valve is followed by a two-phase separator, where the nitrogen in gaseous state is separated from the fluid methane. At the end of the process we will get fluid natural gas i.e. LNG.

The partial purification process justifies an analysis if there is more than 10 Mm^3 reserve depending on the inert gas content.

Gas purification and feed into the pipeline/grid

If no target consumer can be found, the only possibility is to deliver the gas into the grid. To deliver the gas into the grid gas quality should meet the gas standard. Gas needs to be purified using technologies described above, which makes this solution more expensive than deliver gas to a target consumer.

Regarding feasibility, not only cost of carbon dioxide or nitrogen separation should be calculated, but separation cost of other inert component.

Inert gas separation is worth considering if the field has more than 50 Mm^3 reserve.

The other way to achieve demanded gas quality is to implement a mixing circle. Inert gas is mixed with pipeline-type gas or gas from the distribution system to the extent that mixed gas quality meets local grid standard.

In this case fields with very small recoverable resource can be developed for production by connecting it to the existing technology, or supply to low-pressure distribution systems with a simple expansion treatment.

Inert gas production connected to biogas production (Herczeg Jr 2014, www.biogas.hu)

It worth mixing inert gas with biogas both for a target consumer and for pipeline gas as well. The reason is that in case of biogas also the carbon dioxide should be separated in order to secure bio methane to natural gas quality.

Biogas power station has other technological parts comparing to conventional power station. Biogas power station is more costly comparing to a conventional power station. However, permanent biogas production can be secured, and the result is significantly higher revenue under market conditions in long term. The biogas output of the power station is influenced by the fact that it does not generate power during the low demand period of power consumption (overnight) and feed it to the transmission network, because it does not pay back.

Cost of a gas purification technology can decrease in line with increasing capacity, that is the reason raw gas flow volume with biogas could pay for itself. In a given case, implementing a gas technology separately for an inert gas field and separately for a biogas power station may not profitable, but if it is built for both it could be a profitable solution.

During biogas treatment the solid grains, water vapour (ammonia with the water in one step) and hydrogen sulphide are separated. Most part of solid grains and water vapour can be separated at low pressure, and minor grains and hydrogen sulphide should be separated after the pressure boost-up of the gas (feeding iron chloride to the fermenter, or absorption with NaOH and then flow through on activated carbon bed). Then it can be mixed with inert gas and feed into the carbon dioxide separation technology. Very small fields can be developed also in this case if the field is located close to the given biogas plant.

Community utilisation possibilities and estimated project cost, expected payback time

Descriptions and cost shown in the following table (Table 11.1) refer to utilisation of the already treated natural gas (except where marked). In this version payback is secured by the generated power, waste heat, and produced other goods. Fields with low recoverable volume or high inert gas content are able to secure cheap gas source to their consumers at prices 10–20% lower than the consumer gas prices. Motivation cost of consumers to shift toward individual gas source was considered in the calculation (Bauer, Mitev Ariel 2016) (price discount, saving the system usage fee, to increase complexity of supply chain and energy independence).

Table 11.1. Utilisation possibilities for fields with small inert reserve after the gas treatment

Title	Field/well recoverable resource	Investment no gas processing	Expected profit
Power station with gas motor and hydroponics	over 3 Mm^3, min. 6–10 years production period, low inert content, or over 10 Mm^3, max. 30% inert content	Gas motor: 50–250 MHUF Greenhouse (hydroponics): 25,4–40 th HUF/sq m 6,000 sq m hydroponics with gas motor: 280 MHUF	Yearly revenue: 40–60 MHUF Yearly production cost: 10–15 MHUF/year Payback time: 7–8 years
Oxidiser gas turbine power plant, mobile system	over 10 Mm^3, up to 70% inert content. Mobil system may serve group of fields	1 MW system output 450 MHUF	Yearly revenue: 70–90 MHUF Yearly production cost: 10–15 MHUF Payback time: 6–7 years
Central heating	over 3 Mm^3, min 6 years production period, low inert content, or over 10 Mm^3, max. 30% inert content	Re-design gas boiler or gas motor for gas quality: 20 MHUF Boiler replace: 50 MHUF (depends on output)	Cost reduction: 2 EUR/MWh Payback time less than 1 year at gas consumption over 500 m^3/day (heating season)
Target consumers: f.e.: factory (glass, ceramics, bricks, ethanol production, asphalt production, agriculture bakeries with high output	over 50 Mm^3, max. 30% inert content, min. 10 years production period	Processed but not separated gas to target consumers. max. 5 km. Pipeline with low pressure cost 10–20 MHUF/km	Cost reduction 2 EUR/MWh Payback time less than 1 year at gas consumption over 500 m^3/day
Small plant but no heat extra heat use	over 50 Mm^3, max. 30% inert content, min. 10 years production period	min. 3 MW plant, investment: 1,000 MHUF	Yearly revenue: 202 MHUF Cost: 50 MHUF Payback time: 6–7 years
Methanol production using separated CO_2, methane, CO and water	over 600 Mm^3, min. 30% CO_2-content, and water. over 500 Mm^3 recoverable resource with 50–60% CO_2 content	13 billion HUF Investment: gas processing, CO_2 separation and water treatment. Investment period is 3 years at least.	Methanol production: 23 et/years Gas revenue: 37 Mm^3/years Yearly revenue: 3,476 MHUF Yearly production cost: 450 MHUF Payback time: 6–7 years
LNG production, public transport, gas bottle consumers and PB pipeline replacement	over 250 Mm^3, inert gas with max. nitrogen 30%, max. CO_2 10%	3,5 billion HUF Investment time: 2 years Investment: gas dryer with silica gel, and CO_2 separation	Yearly revenue: 980 MHUF Yearly production cost: 440 MHUF Payback time: 7–9 years
Biogas production, using community waste, sewage sludge with inert gas	Recoverable resource less than 3 Mm^3 next to biogas workshop. Possible outcome: methane production with CO_2 separation, or gas motor	Fermenter with gas processing technology to feed 1 MW gas motor: 800 MHUF Connection system for gas washer and distributor: 250 MHUF, or generator with gas motor: 320 MHUF Total investment: 1,050 MHUF – 1,120 MHUF	Yearly revenue: 244 MHUF Cost: 56 MHUF Payback time: 6–7 years
Developing gas mixer system, and gas intake into distributor lines	over 3 Mm^3 recoverable resource, max. 12% inert gas content, or over 50 Mm^3 recoverable resource, max. 12% inert gas content, maximum distance 1–2 km to pipeline connection	Pipeline building: 50 MHUF Developing gas mixer system: 100–350 MHUF total investment: 150–400 MHUF Min. production: 500 m^3/h	Yearly revenue: 210 MHUF Extra production cost (gas processing cost) 27 MHUF Payback time: 7–8 years

Sample projects

The sample projects show capital required to implement a gas technology that produces gas quality demanded by utilisation.

Premises and concepts used for analysing sample projects

Gas price: That gas price was used that is available for producers. In Hungary gas prices are compared to two benchmarks those are so-called TTF (gas exchange in the Netherlands) and VTP (gas exchange in Vienna). Quoted gas prices have high number of versions, this study does not analyse them, as the professional literature covers this issue. Thus we use the annual average of the so-called quarterly forecast prices (generated in January 2018) for the economic analysis. This figure is 17.5 EUR/MWh at TTF, and 18.2 EUR/MWh at VPT. In our analysis we prepare the initial analysis using 0.3 EUR/MWh mark-up price versus TTF (Taylor, Hall 2003).

Condensate price: more or less condensate is also produced/separated with natural gas. In the analysis condensate content average 80 g/m^3 was used (except the sample project for glycol gas dehydration system, where no condensate quantity was assumed). Condensate price was adjusted to Brent price with an average 3 USD/bbl price discount and tanker transport cost was assumed 5 USD/bbl. Actual price is 55–60 USD/bbl, and 55 USD/bbl was used as the lower value in the calculation.

Unit treatment cost without central cost. We calculated with average 6,500 HUF/1,000 m^3 treatment and production cost, which contains cost of the operators, the consumed energy, materials and maintenance. In case of any deviation it is indicated in the description.

Exchange rates:

EUR/HUF: 310 HUF/Euro,
USD/HUF: 255 HUF/$,
EUR/USD: 1,22 $/Euro.

Inflation: 2%

Depreciation/amortisation: we do not calculate with the effect of amortisation onto the profit before taxation, and the analysis was prepared on cash level.

Taxes and royalties: mining royalty and energy tax are the highest payables. Both are regulated in a law decree determining the tax base, rate and deductibles. As a result of the simplified economic analysis we assumed 12% of the revenue as the mining royalty, but no energy tax was calculated, as this tax is payable by the end-consumer or the trader. In case of any deviation it is indicated in the description.

Production mode, gas composition, and the future oil price can have impacts upon the royalty rate. Detailed presentation of these is not within the scope of the study.

Next economic indicators were calculated (Taylor, Hall 2003):

Simplified economic analysis with regard to the sample projects was prepared. Actual projects should be analysed for each field one-by-one, where status of wells, the actual environment (e.g. Natura 2000), and quality of production, etc. should be analysed.

— NPV: net present value, shows the value generated in the project during 15 years retrospectively to the project date and considering inflation. If the value is higher than 0, then the project can pay back within 15 years.

— PI: profitability indicator showing the yield generated by invested 1 HUF during 15 years retrospectively to the present phase.

— IRR: internal rate of return showing the inflation rate or loan interest the project can tolerate. It is also essential that we can compare here whether the project or the realisable interest rate seems a better option.

— Payback time: is the time span when the cost of an investment is recovered.

Other general simplifications:

— Production rate:

Optimum production usually shows a bell-shaped curve with short run-up cycle followed by a slow elongated quantity decline. This mode of production for these fields was not considered, as the individual or target consumer systems should be adjusted to consumption. In case of target consumer systems two main types were applied: so-called base-load, flat consumer systems and temperature-dependent consumer systems. Flat gas off-take was used in the study. Based on field sizes the following time horizon and production rate were used:

— fields below 3 Mm^3: 1,500–2,000 m^3/day production rate and maximum 6-year cycle,
— field between 3–10 Mm^3: 1,500–5,500 m^3/day production rate and maximum 6-year interval,
— field between 10–50 Mm^3: 5,500–14,000 m^3/day production rate and maximum 10-year interval,
— fields between 50–250 Mm^3: 14,000–75,000 m^3/day production rate and maximum 10-year interval,
—field above 250 Mm^3: production rate higher than 75,000 m^3/day.

The study presents 1-1 result among the analyses that can be applied onto group of fields having the given reserve. Worst case scenario is presented when a project still has pay-back based on the indicators. If further investment is required, then the profit of the given field is not necessarily able to ensure the pay-back.

1. Development of a field with less than 3 Mm³ recoverable resource

Economic analysis showed that fields with so small reserve can be developed only with project cost lower than 100 MHUF. The expansion gas treatment is viable technology. The technology has high pressure to cool down the treated gas due to heat dissipated by expansion during the gas pressure reduction. Gas is cooled down at least –8 °C, and water vapour and condensate vapour turns to fluid. If the pressure required for this process is not available the field is unable to reach payback even at the cost of the simplest gas treatment system. Utilisation of daily 1,200–1,500 m^3 gas production can be feasible using special combustion equipment that is not sensitive to gas composition (oxidiser, incinerator), or connecting it to an existing technology.

To this a double separation is needed with the help of a plug catcher. At the beginning of the process the system separates most part of the produced water, then following a two or three phase separation a so-called coalesce separator or cyclone separator follows that captures the liquid drops not in vapour phase. It is also required that the gas is heated through a heat exchanger so that the heavier residual hydrocarbon quantity can possibly enter into the equipment on vapour phase.

This type of fields can be typically utilised in agricultural systems in collaboration with biogas plants.

In case of 100 MHUF investment (e.g. build a connection to boilers heating the greenhouses) the project economic result is:

NPV	9,664,406	**HUF**
PI	1.10	**HUF/HUF**
IRR	6.45	%

Payback period: 4,8 years.

What does this mean?

The process should be analysed from two aspects. If a company wants to secure its own industrial utilisation with the help of a nearby natural gas field and it has adequate boiler technology, then these wells are able to be directly connected to the system and thus the project will pay back during the expected life cycle.

However if the fields are utilised in a so-called greenfield project, then we should not use sellers but costumers prices for analysing the project profitability. The customer's market prices (11) presently move near to TTF+2 EUR/MWh for 20–100 consumer categories. Based on the premises the TTF+2 EUR/MWh price levels means 19.5 EUR/MWh price. This price assumes that the total project cost of well development and combustion technology equipment cannot be higher than 125 MHUF.

PI and IRR indicators show the project will pay back as long as the APR (Annual Percentage Rate) related to deposit interest or financing cost and inflation is less than 6.45%.

The above described assumptions are correct up to 8–12% inert gas content and there is no mining royalty charged after the gas of the field. In case the inert gas content is over 8–12%, these fields cannot be economically developed on its own. Development so small reserve and biogas can be economical even if the inert gas content is 12–30%. The technology is described in "Inert gas production combined with biogas production".

2. Sample project: Gas dehydration with glycol, in or next to well site, field with 3–10 Mm³ recoverable resource

Production rate: 3,500–4,000 m^3/day

Investment: the project can bear the construction of maximum 2 km long pipeline. There is an investment in measurement systems and substitute measurement, power generator and power take-off is assumed.

Name	Value (HUF)
In or next to well site	62,500,000
Producer/connecting pipeline	48,261,818
Collection, processing, preparation station	146,875,000
Technical assistance (planning, supervision, testing)	16,880,000
Offices (expropriation, permits, archeology, compensation, geodesy)	19,880, 000
Sum	**294,396,818**

Operating cost (HUF): we calculated with twice the average operating cost due to extremely low size, i.e. with 13,000 HUF/1000 m^3.

Revenue of sales: no condensate production is planned, revenue comes from natural gas sold.

Revenue during the field life cycle (HUF):

assuming 6-year flat production 512.4 MHUF.

Economic results:

NPV	20,104,296	**HUF**
PI	1.07	**HUF/HUF**
IRR	4.84	%

Payback time: 5.5 years

What does this mean?

It is also relevant here that the project will have payback even with extremely low production rate if the amount of inflation and deposit interest is lower than 4.84%.Utilisation of such fields can be recommended also for target consumers who would like to replace its own consumption with the production of a nearby field.

These can be e.g.:

— greenhouses,

— existing gas motors or turbines,

— supplementing biogas for biogas systems,

— boilers,

— district heating.

This type of fields can be developed as explained in the present description and as presented in the section titled "Development of fields with recoverable resource lower than 3 Mm^3".

Risks: in addition to general risks (well status, size of actual recoverable resource), these projects are very sensitive to the inert gas content of natural gas. In case of higher than 8–12% inert gas content the project is not viable. It is important a low pressure system is needed because the project is unable to cover the cost of compressor eventually arising during the field lifecycle.

3. Gas treatment with automated cooling, 10–50 Mm^3 recoverable resource

It is experienced that the most of these fields have condensate production. Glycol gas dehydration process is not suitable for adjusting the required water and hydrocarbon dew points.

Production rate: 11,000–12,000 m^3/day natural gas and 880– 960 litre condensate per day. In the example a field with 40 Mm^3 reserve is analysed, and a 10 year production is assumed.

Investment: 5 km pipeline is built. This is important because within a 5 km radius, usually there is a system or consumer who/which is able to off-take this gas quantity or a new consumer can be found.

Operating cost: as average operating cost (without compression) is 13,000 HUF/1000 m^3.

Name	Value (HUF)
In or next to well site	62,500,000
Producer/connecting pipeline	120,654,545
Collection, processing, preparation station	712,500, 000
Technical assistance (planning, supervision, testing)	42,200,000
Offices (expropriation, permits, archeology, compensation, geodesy)	47,850,000
Sum	**985,704, 545**

Revenue of sales: planned revenue during the 10-year cycle is 2.436 MHUF.

Economic parameters:

NPV	701,598,422	**HUF**
PI	1.71	**HUF/HUF**
IRR	17.66	%

Payback time: 5.8 years.

What does this mean?

The economic return for these fields is significantly better than fields with extremely small reserve. The IRR is 17, 66% showing that a real yield 15, 66% can be expected during the 10-year.

It is also essential that along with the production rate and the 30% inert gas content assumed the project can provide a positive economic result for a target consumer. No further investment is assumed (off-take) that is gas firing equipment is capable of utilising this type of gas. In this case the payback time is 9.2 years.

Fields with this volume can be developed with glycol gas dehydration, if the gas has maximum condensate content 40 g/m^3.

Risks: the usual hydrocarbon production risk.

4. Gas treatment with automated cooling, 50–250 Mm^3 recoverable resource, supplemented with minor technology for membrane, inert gas separation. 30–50% inert gas (CO_2) content

Production rate: 28,000–30,000 m^3/day

Project cost: a so-called „enrichment" technology should be also built in addition to automated cooling. It may be:

— Amin technology.

— PSA or VPSA technology (solid bed separator or purification system).

— Cryogenic process.

— Membrane technology.

For our sample project we selected the membrane technology, though we have no information on the efficiency and durability of this technology from the practice in Hungary.

Name	Value (HUF)
In or next to well site	62,500,000
Producer/connecting pipeline	120,654,545
Collection, processing, preparation station	2,068,750,000
Technical assistance (planning, supervision, testing)	42,200,000
Offices (expropriation, permits, archeology, compensation, geodesy)	47,850,000
Sum	**2,341,954,545**

Operating cost: extra cost will emerge here compared to average treatment cost due to membrane inert gas separation. Thus we calculated 9,750 HUF/1000 m^3 cost.

Revenue of sales: 4,476.2 MHUF, 10 year lifecycle.

Economic parameters:

NPV	319,455,670	**HUF**
PI	1.14	**HUF/HUF**
IRR	5.14	%

Payback time: 8.6 years

What does this mean?

It can be seen that the inert gas content significantly destroyed the profitability. So it is in vain the recoverable resource is significantly higher than in 3rd sample project, but the results are similar.

In case of inert gas content one more problem may arise. It is the quality of the separated inert gas and the separation. It is experienced that some methane is also separated with the inert component, and this should be deposited or utilised in some way. The following possibilities exist:

— injection into a properly tight hydrocarbon or water reservoir,

— burning the methane content out and utilisation of waste heat,

— utilisation in gas motors or gas turbines,

— combustion in boilers that are suitable for inert gas combustion,

— cleaning the CO_2 from methane through a cryogenic process and utilisation in agriculture, industry or food sector.

Risks: the inert components have significant effect onto the results of project. E.g. if the inert gas contains hydrogen

sulphide, then extra technology is needed for de-sulphurisation. There is a corrosion risk. CO_2 forms with water corrosive medium, the hydrogen sulphide is an aggressive compound also in gaseous state.

If the inert gas share is over 30%, royalty rate declines to 8%, profitability may improve.

5. Gas treatment with automated cooling. Recoverable resource is over 250 Mm^3 with 50% inert gas content. LNG cryogenic and CO_2 separation using PSA/VPSA process can be applied. The inert gas is CO_2 and nitrogen, and CO_2-content is lower than 10%.

This project is able to produce feedstock for LNG/CNG road transport and supplies cylinder gas for large consumers (http://www.panlng.eu/a-projektrol/a-pan-lng-projekt-bemutatasa/). The key features are CO_2 is separation from the gas, and nitrogen separation by cryogenic process. The end-products are:

— high purity liquid methane,
— mixture of CO_2 and methane,
— mixture of nitrogen and methane.

For the calculations we used SZILÁGYI, SZUNYOG (207a, b, c) studies.

Production rate: 83,000–85,000 m^3/day

Investment cost:

Name	Value (HUF)
In or next to well site	62,500,000
Producer/connecting pipeline	120,654,545
Collection, processing, preparation station	4,281,250,000
Technical assistance (planning, supervision, testing)	42,200,000
Offices (expropriation, permits, archeology, compensation, geodesy)	47,850,000
Sum	**4,554,454,545**

Fuel of gas motor generator is the produced waste gas, and it covers technology energy demand.

Operating cost: 6,500 HUF/1000 m^3 as defined in the premise. The mining royalty used was 8% from the revenue.

Revenue: 11,673.8 MHUF during the 10-year production

Economic parameters:

NPV	1,888,488,105	**HUF**
PI	1.41	**HUF/HUF**
IRR	11.28	%

Payback time: 6.9 years

What does this mean?

Assuming very high project cost the project can provide a medium-level payback for the investor. The actual result of the project can be most probably even higher, as we did not calculate with LNG and its quoted price as the end-product, but with the price of the pure methane, as natural gas price. We followed this because the LNG market is not yet typical in Hungary, though it is a dynamically developing segment.

Risks: gas quality is the most critical element of the project. Components, which are not typical for the hydrocarbons, of the natural gas has to be analysed. These components are oxygen, hydrogen, halogen gases and silicate in powder. These components have influence onto the efficiency of gas purification and the cryogenic process, as well.

Location of the usable wells by regions

Using the mineral resource registry we defined fields located close to local governments are selected, and those can be seen on Figure 11.9. It may happen that a field is located on a land that belongs to more than one local government. The fields and wells related to the given local government and their locations can be found in details in the Mining and Geological Survey of Hungary.

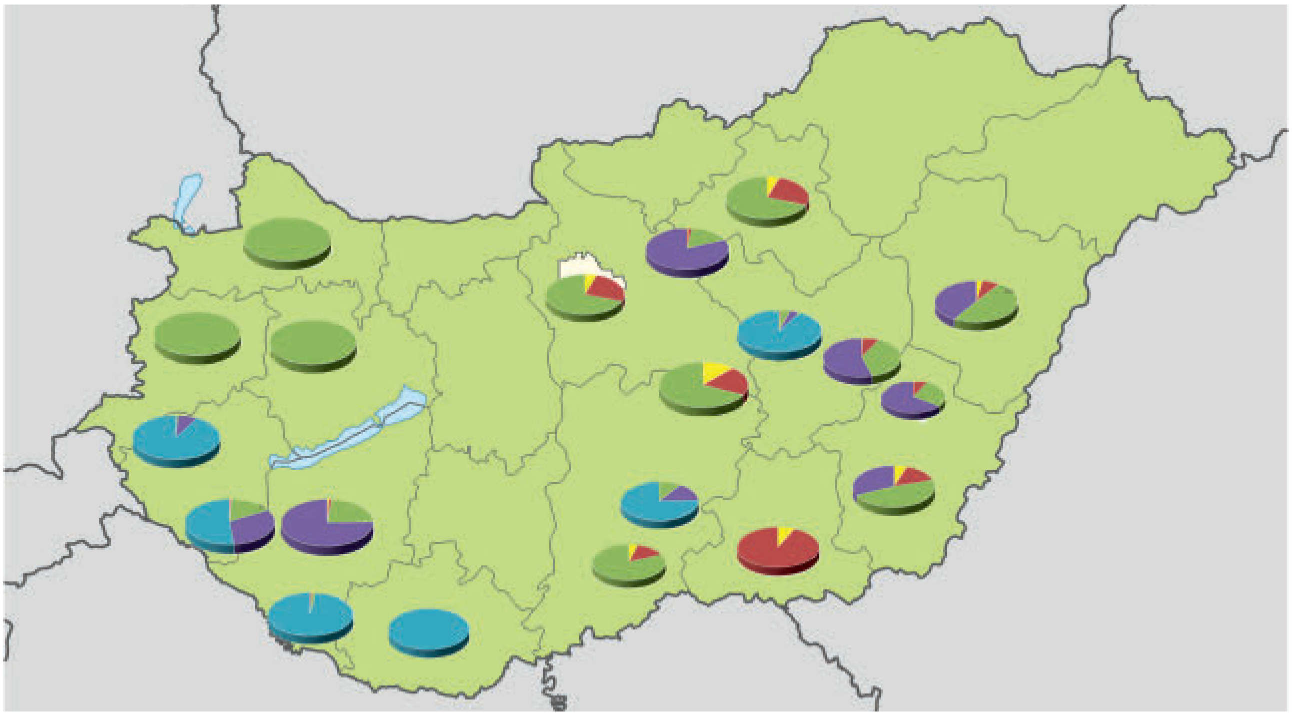


Figure 11.9. Areas with potential gas fields in Hungary based on the study
Legend: yellow: fields below 3 Mm^3, red: fields between 3–10 Mm^3, green: fields between 10–50 Mm^3, pink: fields between 50–250 Mm^3, light blue: field above 250 Mm^3

The map presents location and size of the fields by counties. For the sake of better transparency we broke down this map into county regions, and we indicated the fields, their location and size next to every potential and major settlement.

Fields with inert gas more than 30% have not yet been developed (Figure 11.10). These fields have significant recoverable resource, and some of them enable LNG or even methanol production. This is the region, where fields have Hungary's largest and still undeveloped recoverable resource. The volume of these fields can allow transmission even at greater distance.

On the area there are few small gas resource with high calorific value gas and some major natural gas reserve with high CO_2 and hydrogen sulphide content (Figure 11.11). The fields have more than 200 ppm hydrogen sulphide and more than

Figure 11.10. Settlements in the South Transdanubian Region with potential gas fields based on the study
Legend: yellow: fields below 3 Mm^3, red: fields between 3–10 Mm^3, green: fields between 10–50 Mm^3, pink: fields between 50–250 Mm^3, light blue: field above 250 Mm^3

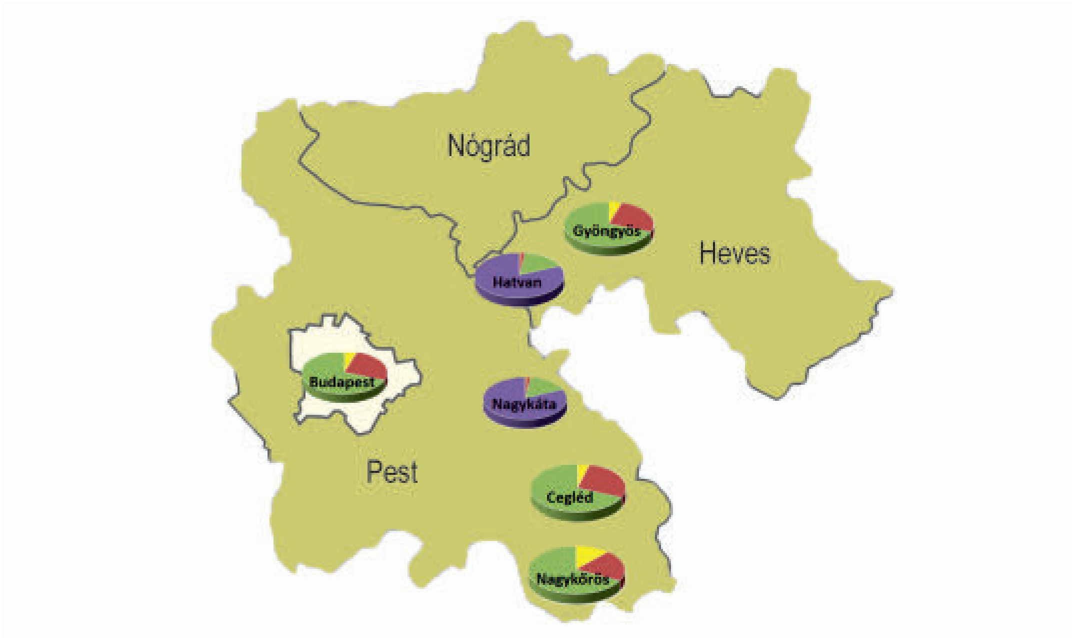


Figure 11.11. Settlements with potential gas fields in Pest and Heves counties, based on the study
Legend: yellow: fields below 3 Mm^3, red: fields between 3–10 Mm^3, green: fields between 10–50 Mm^3, pink: fields between 50–250 Mm^3

50% CO_2 content. It looks that biogas and natural gas combined development is the best option to produce these resource. Gas motors or gas turbines, which are able to manage the extremely corrosive impact of gases, have to be used. Some manufacturers can supply such gas motors.

As the map presents, in this case fields with minor recoverable resource have not yet been developed, because the production infrastructure has a well-established and extremely wide-spread pipeline system (Figure 11.12). The undeveloped fields with major reserve have approximately 50% CO_2 content. Primarily utilisation based on gas motor or gas turbine can be recommended supplemented with greenhouses and heat utilisation, exploiting the agricultural potential of the region.

Among counties in West Hungary Zala County has an extremely wide spread potential (Figure 11.13). Some of the fields are identical with the fields addressed at Somogy County, i.e. they have major reserve with high CO_2 content. There are

11.12. ábra. Settlements in the South Alföld Region with potential gas fields based on the study
Legend: yellow: fields below 3 Mm^3, red: fields between 3–10 Mm^3, green: fields between 10–50 Mm^3, pink: fields between 50–250 Mm^3, light blue: field above 250 Mm^3

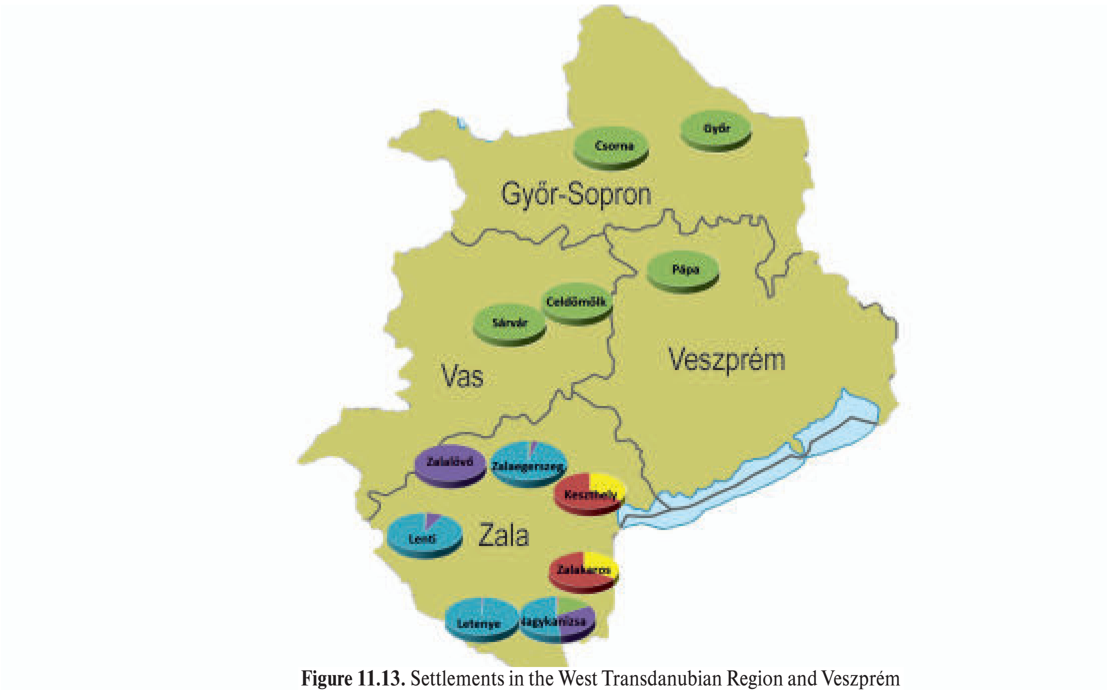


Figure 11.13. Settlements in the West Transdanubian Region and Veszprém County with potential gas fields based on the study
Legend: yellow: fields below 3 Mm^3, red: fields between 3–10 Mm^3, green: fields between 10–50 Mm^3, pink: fields between 50–250 Mm^3, light blue: field above 250 Mm^3

fields with nitrogen content, so we can say that we can find there also field with recoverable resource suitable for operating power stations, producing methanol or LNG. In the other counties we can find medium-size fields with approximately 30% CO_2 content. The area is not very well equipped with production infrastructure, so a field development would need more investment.

There are several fields with major reserves in the North Lowland counties (Figure 11.14). The country's largest field which is suitable for producing 2S quality standard gas is located in this county, but development would establish entry to the grid. The fields could be developed also if a connection to the existing systems is secured, including: power stations, LNG production, district heating supply, bioethanol production, heating gas.

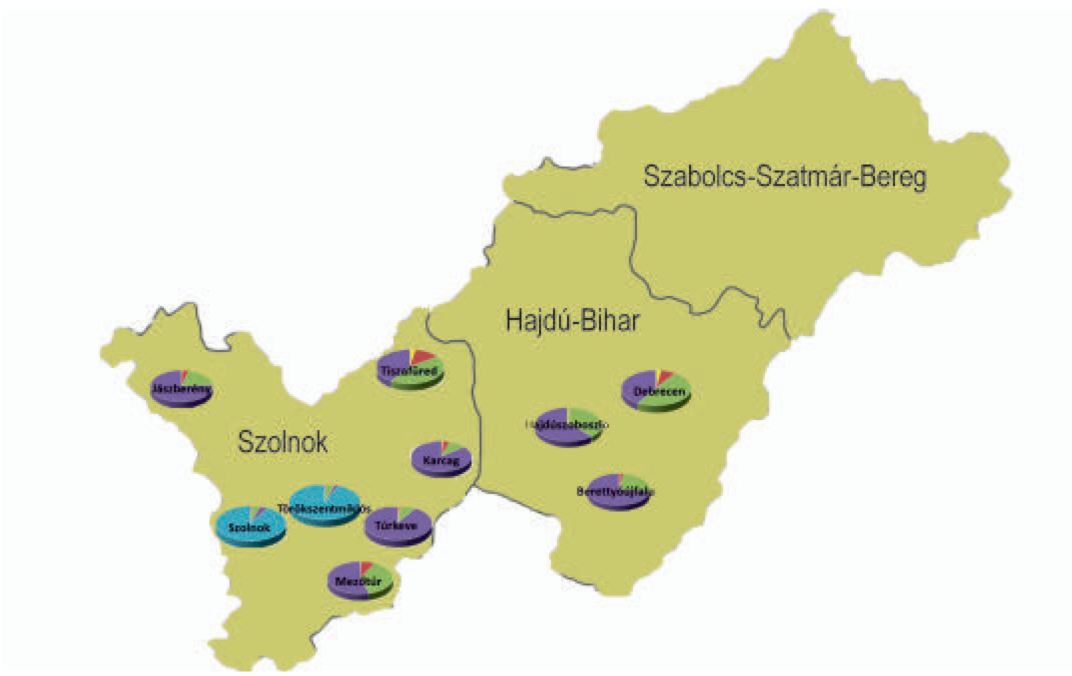


Figure 11.14. Settlements with potential gas fields in at North Alföld Region based on the study
Legend: yellow: fields below 3 Mm^3, red: fields between 3–10 Mm^3, green: fields between 10–50 Mm^3, pink: fields between 50–250 Mm^3, light blue: field above 250 Mm^3

Summary

This chapter discussed the utilisation possibilities of gas wells with production capacity and located in areas belonging to various local governments. Wells are not parts of the national gas supply system.

Connecting these wells into the national network is not profitable under the present conditions, but analysing their local utilisation could be successful with regard to short geographic distances and smaller operating organisation.

In the present assessment we set up various groups in accordance with the quality of recoverable gas and the size of recoverable resource. These groups were analysed and demonstrated, as described using pie charts in the previous chapter, where the relevant field/wells are located and what kind of recoverable resource they have. These fields/wells can be developed using the technology described in the chapter addressing the sample projects and the utilisation possibilities. Gas quality and the applicable gas procession technology can greatly influence how gas discovered in the territory of various local governments can be profitably utilised. The scope of the study does not allow preparing separate proposals for each and every well, but the presented samples and examples can help the local governments to adopt decisions whether running an analysis how to utilise the wells in their territories is worthwhile or not.

An economic feasibility calculation was also prepared for each technology process through sample projects. We finished the analysis of such sample projects at the point where the natural gas could be utilised in so-called conventional or traditional combustion.

It is important to emphasise that no analysis was prepared on the structure and technical status of the underground part of gas wells. Its eventual cost, i.e. to make the gas well able to produce the relevant reserve is not within the scope of economic feasibility calculations. The discussed surface technology regards the well as able and suitable for gas production.

Hungary’s territory was distributed for the gas field analysis in each geographic region as county groups (see: previous chapters). Size of each region was selected in correlation with the distance between the gas source and the end-consumers and the relevant economic feasibility.

Professional background and institutions of exploration–production, status of education and the labour market

12

Zsuzsanna Plank

Institutions of expert training

History of education and training of hydrocarbon mining

The first education institution of the domestic mining and geological exploration was the Mining School (Bergschule) established in 1735 at Selmecbánya, which was later in 1762 re-qualified and upgraded as a higher education institution (Mining Academy – Bergakademie). The Academy soon became an education and research centre with international fame, where the eminent scientists of the age appeared as visiting research fellows, including inter alia Alessandro Volta. Students of this Academy could earn a diploma of engineering, and were highly welcome employees both in domestic and international companies (Figure 12.1).

Figure 12.1. Building of the High School of Mining and Forestry at Selmecbánya (to the left) and the memorial tablet commemorating the establishment in the main hall (to the right). Photo: Z. Lantos

The first written relics refer to the lectures on hydrocarbon engineering education held by Gusztáv Faller, who was during 1850–1860 the professor of deep drilling operations and the relevant. Following the Compromise with Austria the name of the institution changed to Hungarian Royal Mining and Forestry Academy, and in addition to German the Hungarian gradually became also the official language of education.

After the Trianon Treaty the Academy moved into Sopron. This was the city where the first independent discipline on hydrocarbon mining was announced as part of the curricula, named as crude oil- and natural gas exploration, with Simon Papp as the author and lecturer. Later the Hungarian–American Oil Co (MAORT) established and financed its own department supporting domestic hydrocarbon education and exploration development. The first professor of the department was Simon Papp in 1944. In 1948, when the famous MAORT lawsuit was launched (where Simon Papp was the principal culprit) (Figure 12.2) the department, and as a consequence, the hydrocarbon-focused education was terminated. In 1949 the Technical University of Heavy Industry was founded in Miskolc, and the mining and metallurgy education of Sopron was integrated into it. In 1951 Zoltán Gyulay as the head of the Oil Production Department, re-vitalised the education of hydrocarbon exploration, and oil engineering training was also launched in this year, then later in 1967 gas engineering training was also

Figure 12.2. Simon Papp. (Photo: Museum of the Hungarian Petroleum Industry)

Figure 12.3. Main entrance of Miskolc University

introduced. In 1971 the post-gradual engineer training began. Then in 1980 engineer further training courses were launched. The department was at the same time functioning as a research centre, and several industrial inventions started their lives here, for example the first domestic rotary-type drilling and designing the construction of a European oil pipeline.

After the change of the political system significant organisational modifications were going on in the domestic higher education system. The name of the university changed to University of Miskolc (Figure 12.3), and the department was re-organised and thus in 1993 the Institute of Petroleum and Natural Gas was established with two departments (Department of Petroleum Engineering and Natural Gas Engineering), where in 2006 the two-tier (Bologna system) education was launched.

A total of more than 700 students could graduate in petroleum engineering and 300 in natural gas engineering from institutes of domestic higher education. Students can easily find employment in the sectors of the industry, as they are current assets both in Hungary and abroad. We can find experts in senior positions in R+D areas of the petroleum sector and the related administrative and supervisory organisations as former students of Miskolc University.

External supporters of the university education

Industrial sector

On behalf of the industrial sector Mol Hungarian Oil and Gas Plc provides outstanding support to the succession training for the domestic hydrocarbon industry through its renewed programme titled Strategic University Relation launched in 2013. The point of the programme is the Mol Plc provides financial and professional support to the players of domestic natural scientific education and engineer training in order to secure the basis for its own professional succession base and thus to preserve its international competitiveness. With this effort Mol Plc will also develop the domestic higher education and create employment possibilities for the young fresh graduates. The following universities are involved into the Strategic Cooperation:

— Budapest University of Technical and Economic Sciences, civil engineering and chemical engineering,
— Eötvös Loránd University of Sciences (ELTE), Budapest, geologist and geophysicist training,
— University of Miskolc (ME), Miskolc, petroleum and gas engineering,
— Pannon University, Veszprém, chemical engineering,
— Szeged University of Sciences (SZTE), Szeged, chemical engineering and geo-sciences.

In addition to the professional knowledge that can be applied also in practical areas participants in the programme dedicate particular attention to the acquisition and application of professional English proficiency. For this purpose launching of training courses in English language was contributed.

Mol Plc established departments at two domestic universities in order to strengthen its role assumed in higher education: one at Pannon University in 2009 named as Mol Institute of Petroleum and Carbon Technology, and one at the Faculty of Earth Sciences of the University of Miskolc in 2014 named as Mol Institute Department.

For the purpose of maintaining the cooperation with the students the programme contacts directly with the domestic and international students' organisations that are operating at the strategic universities; furthermore Mol's employees and experts participate in carrier-building and other professional events.

Public administration sector

The Mining and Geological Survey of Hungary – MBFSZ, established in 2017 (and its legal predecessor institutions, the Hungarian Mining and Geological Office – MBFH, and the Geological and Geophysical Institute of Hungary– MFGI, formerly Geological Institute of Hungary – MÁFI and Eötvös Loránd Geophysical Institute of Hungary – MÁELGI) are the most significant supporting parties of the petroleum expert training system on behalf of the public administration sector. Employees of institutions performing the responsibilities of public authorities and research institutes were participating in the high-level mining and geo-scientific education almost from the very beginning, i.e. since the establishment as professors, lecturers and consultants in case of thesis.

The MFGI Institute Department was established at the Faculty of Earth Sciences of the University of Miskolc in 2017, which is now, after the organisational transformation, pursuing its activity under the auspices of MBFSZ.

MBFSZ experts organise regular visits and announce summer traineeship programmes and similar training programmes in order to build direct relations with the students.

Institutions of exploration–development

Historic overview

Domestic mining exploration began at the same time when the mining higher education was launched. Mining engineers joined to the activity of the Hungarian Academy of Sciences already in 1840. Loránd Eötvös invented the horizontal variometer in 1891, as the first geophysical instrument on Earth (Figure 12.4).

Figure 12.4. The first test with the Eötvös torsion balance at Ság Hill in 1891. Loránd Eötvös behind the binocular: source https://www.tankonyvtar.hu/hu/tartalom/tamop425/0033_SCORM_MFGFT6001T/sco_01_03.scorm

Main directions of the mining science have always been adjusted to the country's economic position and the demands of the sector. Accordingly, during the first half of the 20th century developments required for the discovery of and production from hydrocarbon fields were dominant. By the 1910-ies the domestic expert pool was developed that was specialised for presenting hydrocarbon reserves and for actions related to exploration and development. The first successful exploratory tests for identifying reserves were performed in 1915 at Morvamező using torsion balance, as it was the pre-eminent instrument applied in geophysical exploration of minerals.

After the Trianon Peace Treaty, exploration of hydrocarbon reserves in Hungary's remaining areas became an issue of key importance. Exploration efforts aiming at automation and modernisation of drilling and production operations and research works for modernisation of transmission got new momentum.

After the Second World War most industries were nationalised so research and development became the responsibility of the state, and the intellectual capacity of the universities was of course involved into the efforts. Later the major mining companies established their own research–development departments and institutions for performing exploration works to support mining or production.

In the 1970-ies and '80-ies the R+D system evolved during the so-called planned economy (Figure 12.5) collapsed by

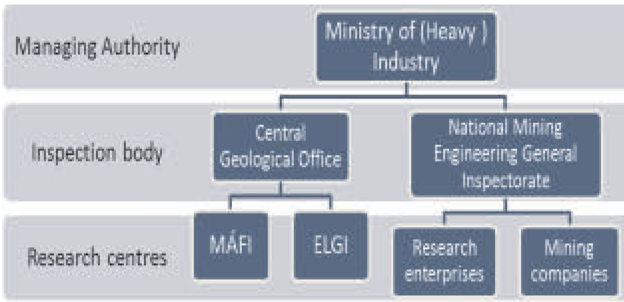


Figure 12.5. Mining R+D system in the 1980-ies

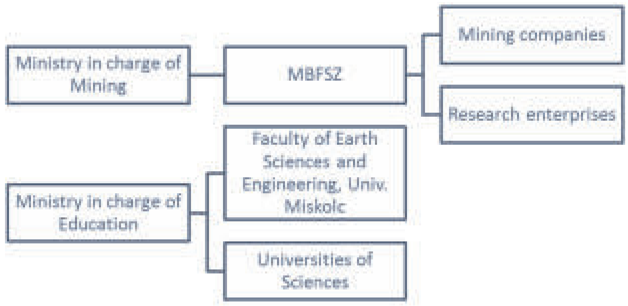


Figure 12.6. Mining and geological R+D system in 2017

the 1990-ies, and long time and several organisational changes were required so that the exploration activity can also receive a proper recognition and prestige in the newly evolving social system. As a by-product of this process, several institutions with remarkable history were nominally wound up, but the high-level scientific activity based on traditions can go on. In the present mining exploration the University of Miskolc can be regarded as the central workshop, whereas the geological exploration–development basis is represented by research fellows of several domestic universities (Eötvös Loránd University of Sciences [ELTE], University of Miskolc [ME], Szeged University of Sciences [SZTE]), and from July 1, 2017. the present Mining and Geological Survey of Hungary (MBFSZ). One novelty in the system is that MBFSZ functions as a state research institution and as a supervisory authority at the same time (Figure 12.6).

Basic and applied research–development tasks were performed at the state research institutes (MTA, MÁFI, MÁELGI, later MFGI and then MBFSZ, and at university departments), while research works related to the industrial development were carried out at various companies.

Institutions of basic and applied research

In addition to the research workshops in the universities several domestic institutions are also engaged in high-level basic and applied research, and the results can be utilised in hydrocarbon production. These research works typically focus on geological, geophysical and geochemical areas.

Scientific works related to hydrocarbon production belong to the X. Geo-sciences Department of the Hungarian Academy of Sciences (MTA). Significant results (e.g.: application of biomarkers in hydrocarbon genetics) were achieved in the MTA Geochemical Research Laboratory that was established in 1955 with the cooperation of Elemér Szádeczky-Kardos, and they were utilised in hydrocarbon production (Figure 12.7). Since 2012, when MTA went through a re-

Figure 12.7. Elemér Szádeczky-Kardos

Figure 12.8. Vibrator measurements in MÁELGI in 2005 (Photo: A. Cs. Kovács)

structuring exercise, the institution has been functioning under the name of Geological and Geochemical Institute, being integrated into MTA Astronomy and Geo-scientific Research Centre.

In addition to the Academy, research pool of the Royal Geological Institute of Hungary (established in 1869), later the Geological Institute of Hungary (MÁFI) and the Hungarian State Eötvös Loránd Geophysical Institute of Hungary (MÁELGI) (established in 1907) continuously contributed the development of hydrocarbon exploration/production providing significant results achieved in basic and applied research in the areas of geology, geophysics and a geochemistry (Figure 12.8).

The research–development activity in Hungary looks back to a nearly 150-year history and presently it is pursued under the auspices of the legal predecessor Mining and Geological Survey of Hungary (MBFSZ).

Institutions of industrial research

The industrial research institutions evolved from organisational units of institutions performing exploration and production of hydrocarbon reserves during the second half of the 20th century.

The Oil and Gas Engineering Company (Olajterv) was established from OKGT's central engineering and development organisation during the 1960-ies. The company was transformed into a limited-share enterprise in 1991, and later it became the largest pipeline infrastructure building company in the country. Its main shareholder has been Mol Plc since 2017.

Through its legal predecessor the Hydrocarbon Research and Development Institute (SZKFI) is looking back to a history of more than 100 years. It has achieved significant results in research of methodology of geological exploration and production and in development of equipment and technology.

Maszoil Geophysical Co was founded for executing surface geophysical exploration necessary for hydrocarbon production in 1952. The company was a joint venture in Soviet–Hungarian ownership and it became a 100% state owned company in 1955, establishing the Petroleum Exploration Company at the same time. Its Department of Surface Geophysics was re-organised in 1957 under the name of Petroleum and Seismic Exploration Branch when OKGT was founded. Exploration projects were implemented applying gravity, alternate and direct current as well as telluric methods in addition to the seismic methods prevailing in the hydrocarbon industry. After the change of the political system the company was several times transformed, and then between 1993–2013 was renamed as the Geophysical Services (GES) Ltd (Figure 12.9).

Figure 12.9. Drilling rig (Photo: B. Kemény)

Deep drilling geophysical exploration projects emerged still during the MAORT era, then Maszoil, and later OKGT maintained an organisational unit for developing well tests, interpretation and perforation technologies. The Factory of Geophysical Instruments and later GAMMA Works Geophysical Branch also developed instruments. The deep drilling geophysical units were integrated when the Geophysical Exploration Company was established, which was renamed as Geoinform Ltd. in 1993. Presently this enterprise is a subsidiary in Mol Group, and performs dynamic activity in the field of industrial R+D.

System of institutions of the domestic hydrocarbon exploration and production

As set out in the Mining Law, hydrocarbon exploration and production is a state monopoly, and the state can transfer this right under a concession contract for a definite period of time onto other legal entities or natural persons. Such exploration/production rights can be acquired since 2013 through a concession tender process (bid round). The minister responsible for the area approves the decisions on concession rights, and MBFSZ provides the professional background materials (e.g.: areal delineation, sensibility and vulnerability assessments).

Representatives of the sector are also involved into the process of selection of concession blocks and the tender process, thus a transparent and professionally robust tender system was developed, unique in the region, and thus result could be to

high extent achieved thanks to the involved contractors' active participation. Average nearly 4–5 companies submit bids in a year. Production has been going on in such blocks since 2015. The number of hydrocarbon producing fields has been dynamically rising: 236 fields were in operation in 2012, and 317 in 2016. At the same time the number of companies engaged in hydrocarbon production and holding licenses from the mining supervisory authority increased from 13 up to 20.

The leading institution of domestic hydrocarbon exploration and production is the Hungarian Oil and Gas Company (Mol Plc) founded in 1991, in which the Hungarian State holds a significant number of shares. Mol integrates every segment in the petroleum industry from exploration through production and refining to residential sales.

Labour market background*

Companies pursuing mining–production operations (Geoinform Deep Drilling Services Ltd) can offer the main employment possibility for domestic experts. The number of enterprises has not changed significantly, rather it has been slightly decreasing in the past 15 years. There was a major change in the size of the companies: while in 2008 the average headcount of a subsidiary controlled by an international parent was 37, this figure was only 17 in 2014. During the same period the average headcount of domestically owned mining companies was between 8–9.

Though enterprises carry out intensive search for domestic experts as they are excellent and qualified specialists, they may face various difficulties when looking for jobs. In 2016 the share of vacancies in jobs for diploma-holders in the industry was 0.4%: it was far lower than the average in the national economy, i.e. 2%.

Experts who earned their diploma in the internationally widely known and recognised centre of the domestic hydrocarbon mining education and training at the University of Miskolc are primarily employed in Middle-East countries, but they are also known and accepted in the petroleum sector of the CIS and countries in the Far East.

Professional organisations

Among domestic professional organisations in the mining industry the National Hungarian Mining and Metallurgy Society (OMBKE, established in 1892) has the longest historic traditions. The organisation has been maintaining significant international relations and its dedicated goal are to ensure interest representation for the industry and develop domestic industrial policy. Support to professional development, promotion of publication activity and organisation of professional events receive for exchange of experiences and consultations are the most important. The members are forming six faculties, and the Faculty of Petroleum, Natural Gas and Water Mining represents the petroleum mining sector.

The Hungarian Mining Association (MBSZ) is the largest representation organisation for domestic mining employers. It is a member of several significant domestic industrial and professional representation groups and has professional relations with Miskolc University and MBFSZ through cooperation agreements, and collaborates with Mining Faculty of the Hungarian Chamber of Engineers. It is also focusing on representation on EU level and participates in the work of several EU industrialist organisations through its member companies (e.g.: OPG International Association of Oil and Gas Producers). The Hydrocarbon Mining Exploration and Production Faculty represents the petroleum sector.

Professional scientific research organisations related to the sector include several sections of the Hungarian Geological Society (established in 1848), the Society of Hungarian Chemists Mineral Oil and Petrochemical Section (established in 1907), and several sections of the Society of Hungarian Geophysicists (established in 1954). MTA Miskolc Academy Committee (MAC) has a mining section as the sole organisation in Hungary having such section and representing the sector on regional level in the scientific life.

The Hungarian Chamber of Engineers Gas and Oil Professional Faculty represents the engineers working in the sector.

The Hungarian Oil and Gas Museum at Zalaegerszeg

As a result of wide cooperation the Transdanubian Oil Museum was inaugurated on September 27, 1969 at Zalaegerszeg, which was functioning since March 26, 1971 as the Hungarian Museum of the Oil Industry. Since June 26, 2013 the Museum has been serving the Hungarian culture under the name of Hungarian Oil and Gas Museum (MOGIM) covering the entire Carpathian Basin as its area of collection.

The Museum was established with the purpose to collect, cherish, scientifically process and exhibit the memories of the hydrocarbon industry, technique, technology, economy and mode of life. The museum is responsible for keeping the collections and organise exhibitions presenting and edit publications publicising the historic documents and memories of

*After data of Hungarian Central Statistical Office.

the Hungarian crude oil and natural gas industry and water extraction (Figure 12.10). The museum has a collection of technical memorabilia, documents of industry and technology history, historic collection, photographic, film and video archive, collection of pieces of fine arts and applied arts, Zsigmondy Vilmos Collection (objects, pictures and documents related to water extraction and water well drilling), library, data warehouse, as well as mineral and rock collection.

The permanent exhibition (presently under reconstruction) established at Vecsés, next to Budapest in 1995 should be specifically mentioned, where visitors can see equipment and documents of crude oil and natural gas transmission by pipeline. The museum operates an LT–3 tank station as an industrial monument at Lovászi. At Bázakerettye visitors can see an industrial history exhibition and Ernő Buda memorial room in the operating building of a BT–2 tank station.

In its collections the museum keeps documents, photos and objects not only for the oil and gas industry, but similar objects for the entire Hungarian industry, its universal technical history, including also solid mineral mining.

MOGIM publications, reports, volumes and books describing the history of the oil and gas industry prepared with oil and gas experts received very wide recognition in the petroleum sector and in the area of museology.

MOGIM is an eminent institution of the network of Hungarian museums, as Hungary's second most significant specialised museum and Europe's second most important petroleum museum. Professional work, scientific and research activity, temporary and moving exhibitions, and more than 20,000 visitors annually visiting the exhibitions can clearly prove this success. The museum building is located at Zalaegerszeg, in Wlassics Gyula street, while the open-air exhibition is situated in the Falumúzeum street.

Figure 12.10. Saint Barbara statue at Zalaegerszeg MOGIM open air exhibition

Data supply of the Mining and Geological Survey of Hungary supporting hydrocarbon exploration

Gábor Kovács, László Vértesy, László Orosz, Márton Bauer, Ágnes Gulyás, János Kiss, Pál Lendvay, Vera Maigut, Zsolt Kovács

Registry of mining areas (BATER)

The registry database contains the most important data of the mining plots and exploration areas — collectively: mining areas. Article 26/B § (3a) of the Mining Law and Article 4. § (2) 18. a) of the Government Law Decree 161/2017. (VI. 28.) on the Mining and Geological Survey of Hungary (MBFSZ) prescribes this obligation for the Survey. Resolutions on first and second instance issued by MBFSZ and the mining departments of those five county-level government offices that perform also mining supervision tasks (as well as their legal predecessors), provide the basis for the registry. The registry contains all important resolutions for every mining area starting from granting the exploration right or the establishment of the mining plot through modification, division and merging of mining areas and approval of technical operation plans (TOP) until the acceptance of the final report and the cancellation of the area. Data of resolutions related to terminated (relinquished, expired, deleted) areas can be also retrieved from the registry.

The BATER database contains as attribute data — inter alia — the corner point coordinates, the height above see level of the floor and cap planes of the given mining plot or exploration area, as well as name and availabilities of the mining contractor, the type of the minerals to be explored or exploited, and the term of the license.

On its website MBFSZ regularly publishes the registry of mining areas with valid licenses in the form of maps of various digital formats (pmf, pdf, kmz).

According to the registry, there were about 270 hydrocarbon mining plots and 25 exploration areas in Hungary as of 2017 December.

Hungarian State Geological, Geophysical and Mining Data Center

The Hungarian State Geological, Geophysical and Mining Data Center (MÁFGBA) operates within MBFSZ and is responsible for collecting, storing, preserving and processing manuscript or low circulation reports and other professional documents prepared by institutions, companies, and experts performing geological exploration and mining activity. Providing these materials to interested parties within a properly developed and modern regulatory framework is also an important task for MÁFGBA. As a result of several decades of continuous collecting efforts by the Data Center and its legal predecessors, as well as obligatory data delivery prescribed by laws, and the transfer of data held in archives of state companies closed in the 1990s, the country's largest collection of geological and mining documents has been formed.

The mentioned document portfolio can be divided into two major parts:

1. Reports (exploration, methodological, field measurement, mapping, and other reports, analytical results), which also contain large number of maps, logs and other graphical annexes.

2. Drilling documentations (drilling logs, core descriptions, well books, hydrogeological logs, etc.).

The registry of the Data Center presently contains more than 160,000 reports and nearly 190,000 drilling documents. The document stock consists dominantly of paper-based documents, and only a small part is available in digital form. However, the rate of the latter is permanently growing as the mining contractors and research organisations hand over most of the documents in digital form in the framework of the obligatory data delivery — e.g. majority of geophysical data are sent in digital form to the Data Center. Furthermore, scanning works performed to comply with data provision needs also contribute significantly to the growth of digitally available data stock.

In addition to standard-size (A4) documents the Data Center also manages large-size (A3–A0) maps, atlases and other documents, as well as microfiches and digital data storage media (CD, DVD, cartridges, HDD). Readers can find the necessary documents with the help of various registry databases or conventional catalogue system.

Majority of documents and data are accessible for the public. Exceptions are data classified as decision-preparatory information and as business secrets. Article 25. of the Mining Law (adopted on January 11, 2015) prescribes that data acquired during exploration should be regarded and treated as business secret until the exploration right is terminated (or until the final decision is approved on the application for establishing a mining plot), whereas data obtained within the

mining plot, until the mining right is terminated but no later than the end of a three-year period starting from the deadline of the data supply obligation. Data with such limited accessibility can be also studied with the data-owner's consent.

The documents can be studied, and notes can be made about them, free of charge in the reading room. Photocopies or scanned copies of the paper-based documents, as well as digital copies of the digital data can be requested for data service fee. Databank fee chart is available on the website of the Service.

Documents deemed essential from hydrocarbon exploration and production aspects are hydrocarbon exploration final reports, drilling logs and closing reports of exploration wells, field and processed data of geophysical — primarily seismic 2D and 3D — acquisitions, and acquisition reports, as well as geophysical logs of drillholes.

Data room for concessioners

Contractors submitting hydrocarbon concession bids have the option to use data room services in the MBFSZ building located in Columbus street, Budapest. Data Center services have been extended by establishing a workstation where contractors can view processed seismic profiles and field data available in digital format. In addition to individual acquisitions, logs and 3D seismic datasets, in many cases other accompanying data (e.g. velocity, sps) are available on the workstation. OpendTect software can be used for looking into the processed seismic data. SeiSee programme helps to view SEG-Y data, while SegDSee programme is used for studying SEG-D data in the data room.

Databases

Geological and geophysical data, measured and collected by the Survey and its legal predecessors (Figure 13.1) are also available for and can be used by experts who do not work for the Survey. Most of these data is available in structured database equipped with metadata, in a retrievable format. General survey metadata on exploration works are accessible on the website of the Survey also in a separate registry. The following section presents the data systems that are most frequently requested for purposes of hydrocarbon exploration.

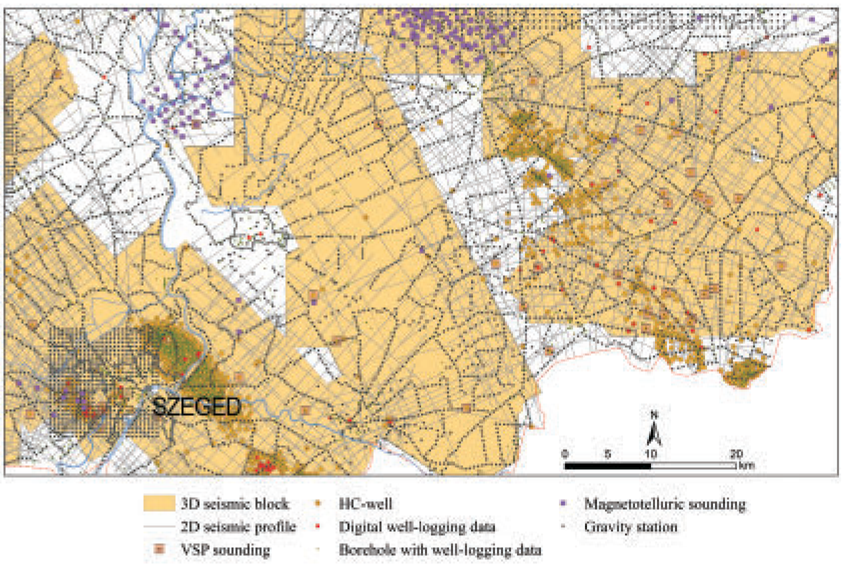


Figure 13.1. Geophysical survey map of Hungary (detail)

Seismic database

The database contains field and processed data of seismic 2D and 3D measurements performed in the area of Hungary irrespective of contractor and the purpose of the acquisition. Previously Eötvös Loránd Geophysical Institute of Hungary (MÁELGI), and market players performed most of the 2D acquisitions with the purpose out of mineral exploration, typically hydrocarbon exploration. Majority of 3D acquisitions were performed for hydrocarbon exploration purposes, achieving nearly 20% national coverage by 2017-end. Significant quantities of seismic materials are available in raw field format, and also in processed, migrated format.

Number of objects: 3D block, processed: 98 pcs, 3D block, field acquisitions: 107 pcs, 2D lines: 6,577 pcs, 2D processed lines, in SEGY format: nearly 3,200 pcs.

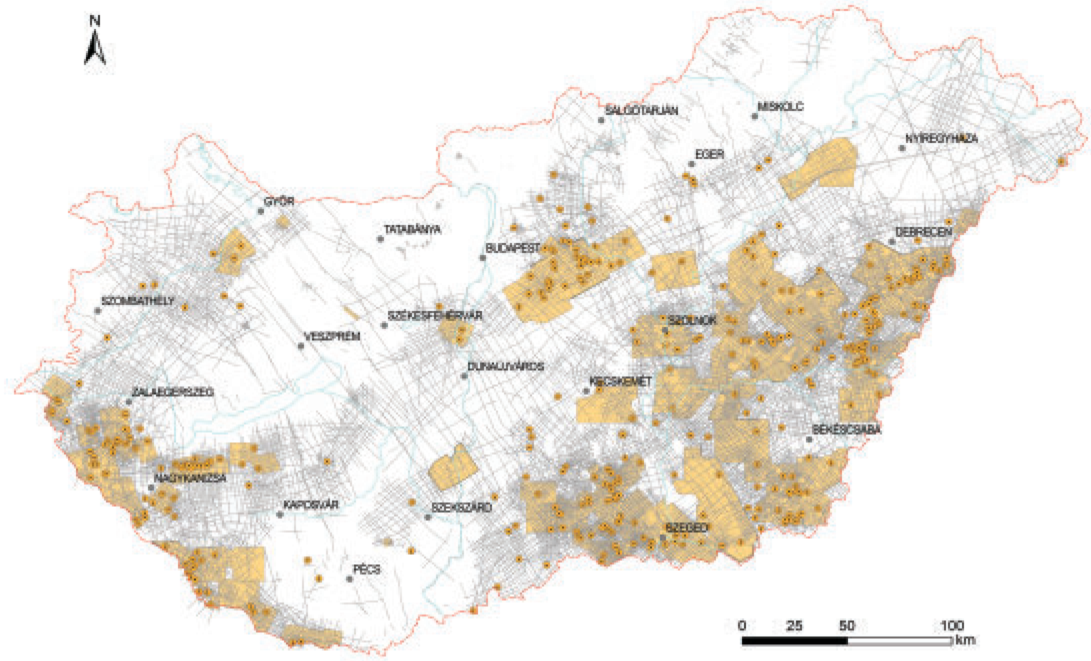


Figure 13.2. Seismic survey map of Hungary
Orange polygon – 3D seismic acquisition block, grey line – 2D seismic profile, orange circle – VSP data

Data format: SEGY, SEGD, load factor of the database is nearly 85%. Coverage: all Hungary, on mountainous area rare (Figure 13.2). Metadata last updated: December 1, 2017. Source: MÁELGI acquisitions; mandatory data supply for the Hungarian Mining and Geological Office (MBFH), and MBFSZ; Mol Hungarian Oil and Gas Plc and its legal predecessors. Update: annually.

Geophysical well log database

In Hungary Schlumberger Company carried out the first logging job in 1935, then regular domestic logging started in the 1950-ies. Later developments in Hungary were some 10 year lagging behind international standards, so computer-

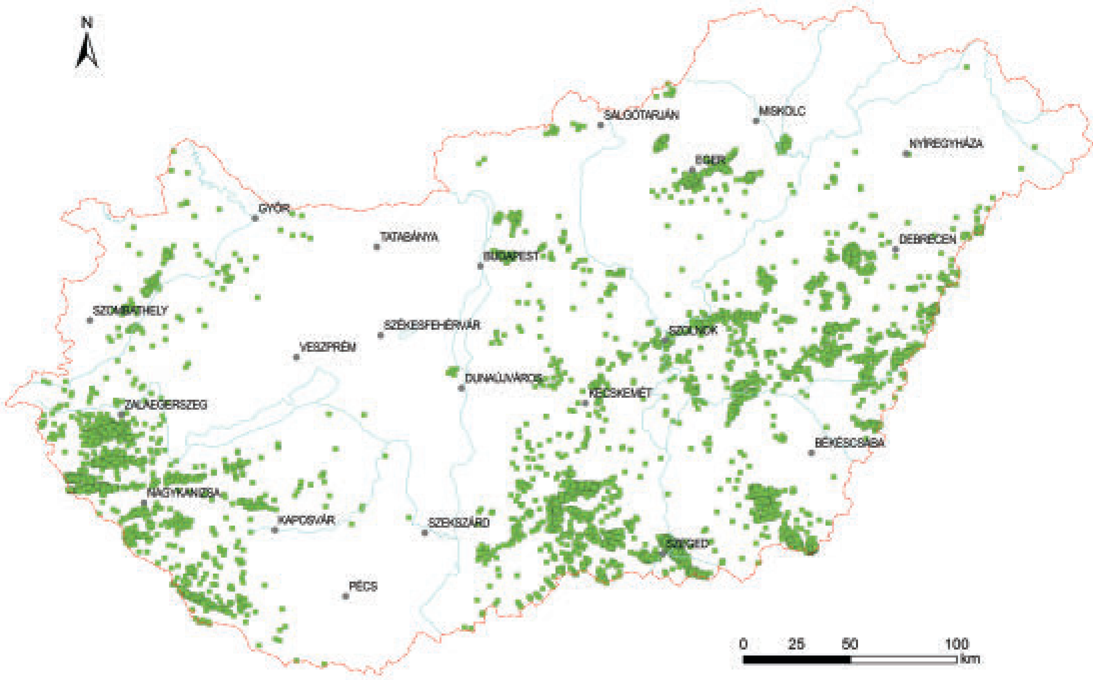


Figure 13.3. Location map of hydrocarbon wells with geophysical well logs in Hungary
green points: hydrocarbon wells with geophysical well logs

supported data procession started at the end of the 1970-ies, and digital field data acquisition was extended during the 1980-ies. The number of informative objects related to hydrocarbon exploration is nearly 7,200, among them 1,700 are digital. Metadata last updated: December 1, 2017.

Data format: las file. Coverage: all Hungary (Figure 13.3). Source: MÁELGI acquisition; mandatory data supply to be submitted to the former Hungarian Geological Service (MGSZ), MBFH and MBFSZ; Mol Plc and its legal predecessors. Update: annually.

Gravity database

The database contains data of land gravity survey using gravimeters (acceleration, latitude correction, elevation correction, Bouguer-plate correction, topographic — close — and remote field effect correction).

MÁELGI performed most of the large scale acquisitions along the motorable roads that cover the entire area of the country, detailed acquisitions were ordered by the industry. Acquisition data were captured during the period between 1950 and 2007. The available average accuracy of the acquisitions was 0.1 mGal.

Resolution of large scale acquisitions ~2.8 points/km^2, in case of detailed acquisitions 6 points/km^2. Based on the data base parameter maps can be constructed on any part of the country (Figure 13.4). Number of objects: 388,067 points.

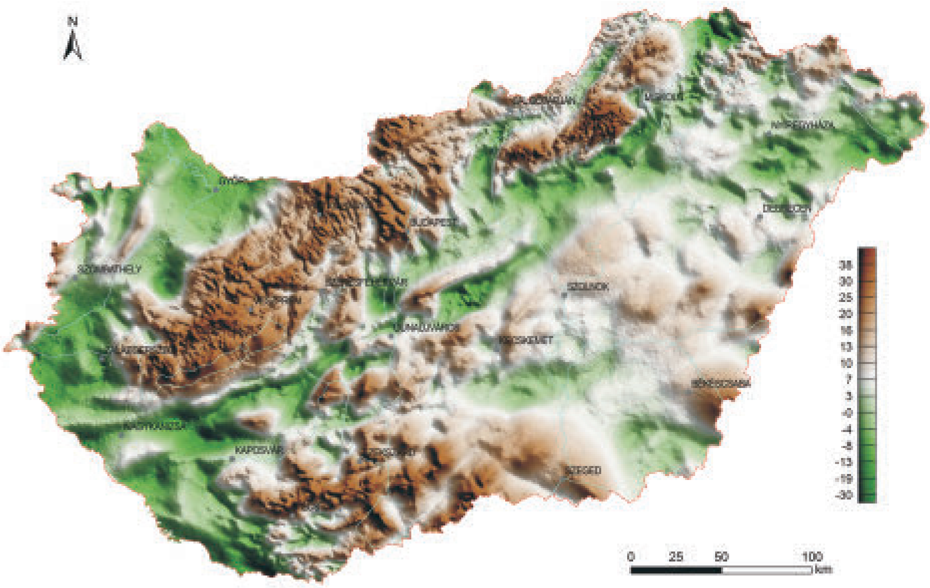


Figure 13.4. Gravity Bouguer anomaly map of Hungary

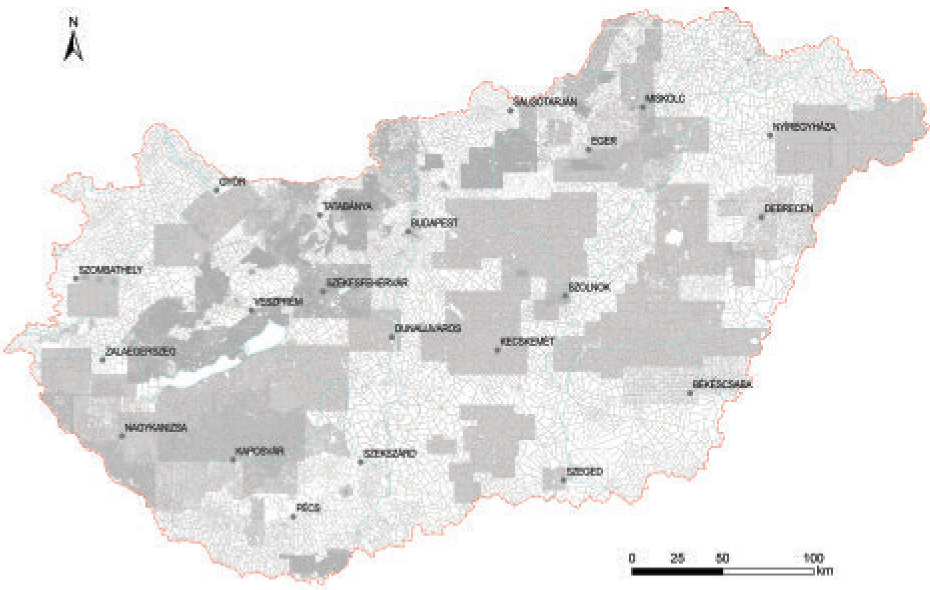


Figure 13.5. Gravity survey map of Hungary: 388,067 measurement points

Format: ASCII. Load factor: 99%. Coverage: all Hungary (Figure 13.5). Last updated: January 1, 2017. Source: MÁELGI acquisitions; OKGT/Mol Plc acquisitions; mandatory data supply to be submitted for MBFH and MBFSZ. Update frequency: semi-annual.

Magnetic database

The database contains acquisition and corrected data of geomagnetic land survey (normal field correction, standardised magnetic ΔZ and ΔT data). The large scale ΔZ acquisitions covering the whole country were performed by MÁELGI, and most of detailed ΔT acquisitions by commercial parties for the hydrocarbon exploration. Acquisition data were captured during the period between 1949 and 2004. Accuracy of the data: 0.1 nT. Resolution: ΔZ ~0.8 points/km^2, ΔT 6 points/km^2.

Based on the data base, parameter maps can be constructed on any part of the country (Figure 13.6). Number of stored objects: ΔZ: 76,705 pcs, ΔT: 137,817 pcs.

Format: ASCII. Load factor: ~50%. Coverage: ΔZ all Hungary, ΔT various exploration areas, all together nearly 20,000 km^2 (Figure 13.7). Last updated: January 1, 2017. Source: MÁELGI acquisitions; mandatory data supply for MBFH and MBFSZ. Update frequency: annually.

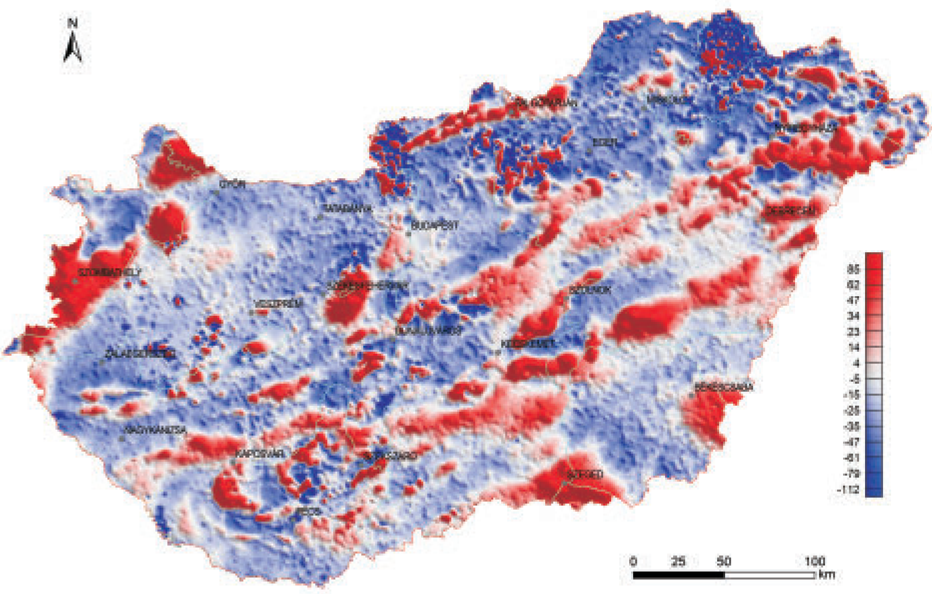


Figure 13.6. Magnetic ΔZ anomaly map of Hungary

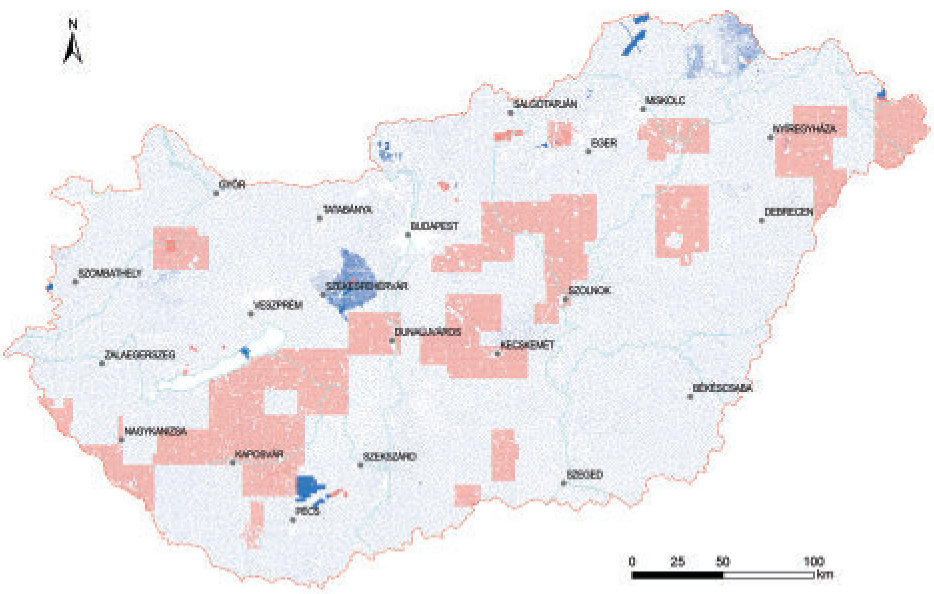


Figure 13.7. Magnetic survey map of Hungary (blue– ΔZ, red – ΔT)

Magnetotelluric database

The Magnetotelluric Data Base contains magnetotelluric acquisition measured data by ELGI–MFGI, Mol Plc and MTA (Hungarian Academy of Science). The data base contains magnetotelluric tensor elements of 5,021 stations by processing 4068 magnetotelluric time-series dominantly in the generally accepted EDI standard format (WIGHT 1988) files. Since 2015 the acquisition time-series have been also recorded into the database. Based on soundings material and structural homogeneity of major depths can be explored. Number of the stored objects: 5,021. Format: EDI. Load factor: 99%. Coverage: all Hungary (Figure 13.8). Last updated: December 1, 2017. Update: annually.

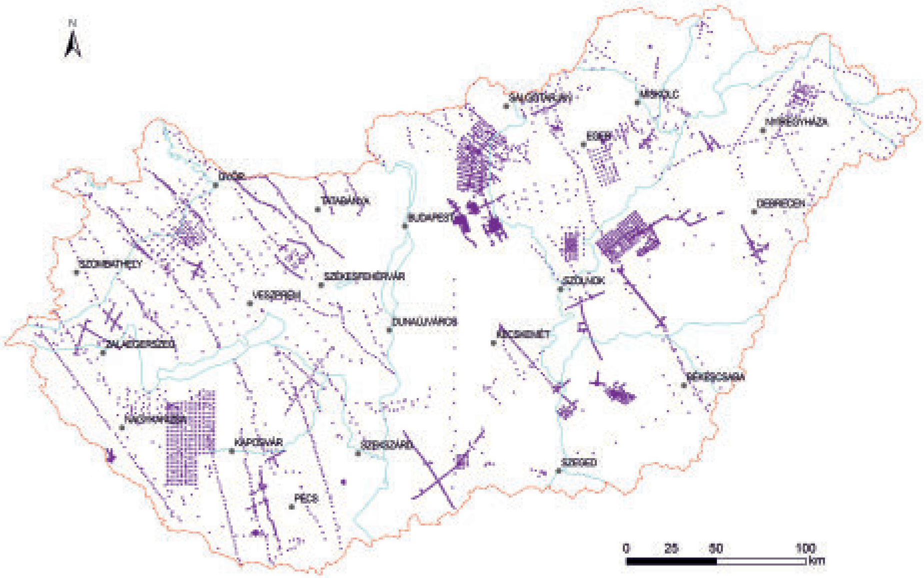


Figure 13.8. Magnetotelluric survey map of Hungary

Airborne geophysical database

The database contains Hungary's available airborne geophysical data from the period between 1967–2005. During 1967–69 nearly 40% of the country was covered through data acquisition campaigns, mostly by Russian experts exploring for uranium, typically using 500 m line spacing. These provided magnetic and radiometric data, ensuring much higher data density than was available through surface data acquisitions. After 1989, local data acquisitions was performed locally using the most up-to-date digital recording solutions, including also electromagnetic channels. The database contains

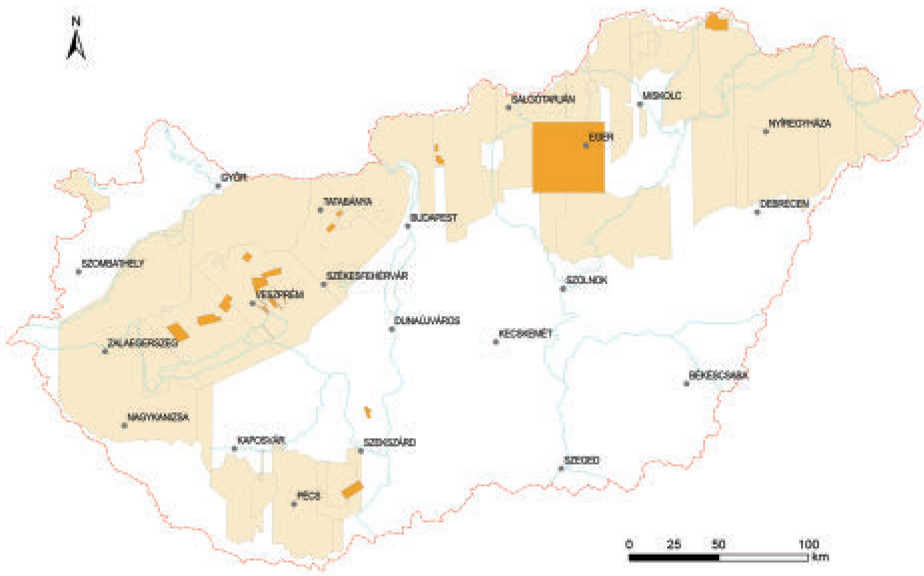


Figure 13.9. Survey map of digital complex geophysical acquisitions (brown symbol) after 1989 and area of the Russian radiometric and magnetic acquisitions (orange polygon) in 1960s

magnetic ΔT and radiometric (potassium [K], equivalent Uranium [eU], equivalent Thorium [eTh] and Total Gamma Intensity [TC]) parameters named as „Russian acquisitions" (in various procession levels), as well as digitally recorded data showing electromagnetic (EM) parameters using VLF or 2–3 frequencies as well. Density of the latter data is higher by one order of magnitude. These data were prepared only for certain areas (marked with brown colour on Figure 13.9).

The number of the stored objects are 657,662 magnetic ΔT grid points. Load factor: 75%. Coverage: regional level. Radiometric and magnetic data acquired in 1965-69 are available for nearly 40% of Hungary's. Locally available with higher resolution rate (Figure 13.9). Last updated: January 1, 2017. Source: acquisitions MÁELGI and MÉV (former Mecsek Ore Mining Company, today: Mecsekérc Zrt.); mandatory data supply for MBFH and MBFSZ.

MBFSZ GeoBank — Hungarian Geological Symbols and Hungarian Well Database

Data base named as MBFSZ GeoBank contains data of wells drilled in Hungary, as well as information and symbols of geological units separated by the Survey and its legal predecessor during the documentation of geological mapping and drillings and applied on geological maps and in well database. The database contains 270,000 drilling records. It can provide their header data, including well sign, number, the settlement where the well was drilled, the EOV coordinates of the drilling point, the well completion date and the drilling depth. Hungary's drilling point location map was prepared using these data. (https://map.mbfsz.gov.hu/furas/).

The presently available types of information:

— drilling sequence of layers: any number of sequence of beds can be stored for every drilling, including the date, project of the re-assessment, and the party performing the assessment;

— core data: detailed data of available drilling cores (storehouse, shelf, etc.);

— in case of shallow drilling: grain resolution, geochemical data;

— groundwater observation and measurements: water chemistry, organic material content, utilisation data, etc.

One of the basic pillars of GeoBank is the table containing geological units. This is the presently effective and consistent Hungarian Geological symbol set, which contains the name, index, age category, facies, lithological description of every geological formation and other data required for the work in the Survey. Data of drilling sequence of formations also refer to the records of the Hungarian Geological Symbols.

The GeoBank is bilingual: all data are available in Hungarian and English. It also contains a retrieval and management surface browser based. Results gained from the retrieval programme can be exported from the system in xls format.

Only MBFSZ employees have full access to the database. Others may use the database with limited access following a registration using this link: https://mbfsz.gov.hu/geobank. Only header well data and no sequence of layers data can be retrieved. Data other than header data (sequence of layers, groundwater level, core data, project information, etc.) presently are not accessible even following registration on web surface. Detailed drilling data — if there is any relevant report or publication — can be personally studied in the data center or in the libraries.

Data request: Mining and Geological Survey of Hungary (MBFSZ), Division of Geological and Geophysical Data Center, H–1145 Budapest Columbus u. 17–23.

Map, geophysical and drilling data supply through web surface

MBFSZ map server can be reached on the following link: map.mbfsz.gov.hu url. Contacting the map service page on the website several informative geological and geophysical maps can be reached showing data for hydrocarbon exploration that represent the information mass at the Survey.

MBFSZ supports work in own desktop geographic information environment with data supply using OGC = Open Geospatial Consortium standards and ArcGIS map services. Several maps are available also in WMS and WFS services format, so these can be reached using several geographic information programmes.

The following maps are presently available:

Drilling point locations of Hungary, 1:100,000,
Basic geological sections of Hungary, 1:100,000,
Geological map of Hungary, 1:100,000,
Geological atlas of Hungary, 1:200,000,
Geological map of Hungary, 1:500,000,
Geological map of deep subsurface of Hungary, 1:100,000,
Geological Map of deep subsurface of Hungary, 1:500,000,
Pre-Cenozoic geological map of Hungary, 1:500,000,
Geophysical measurements map of Hungary 1:100,000.

Services that can be ordered

Contractors interested in hydrocarbon exploration in Hungary can get support from several decade-long experiences of experts and knowledge base of MBFSZ and its legal predecessors, the Hungarian Office for Mining and Geology the Geological Institute of Hungary and the Eötvös Loránd Geophysical Institute of Hungary. The Survey prepares data package by orders with the help of the country's most complete data system. Supported with special expertise it accepts

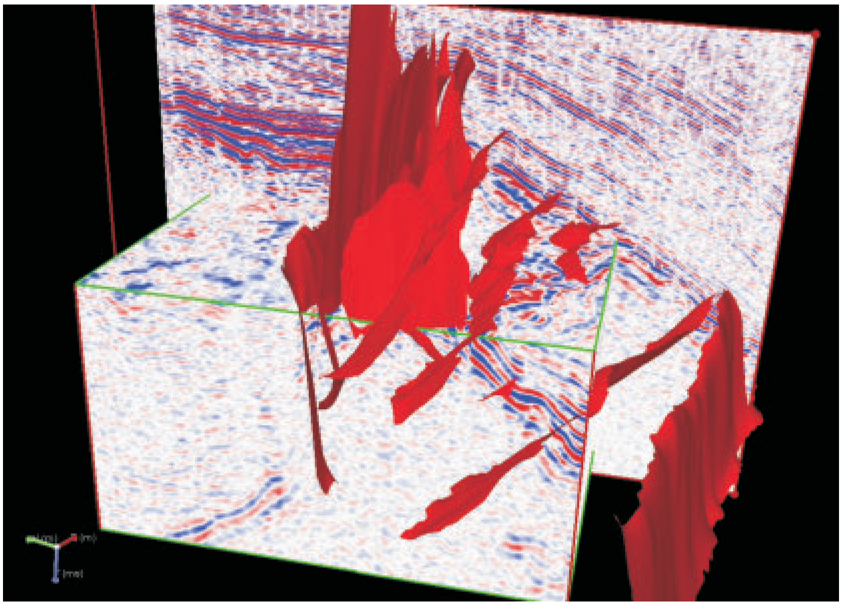


Figure 13.10. Seismic structural model prepared for reservoir assessment (Source:MFGI)

orders for preparing exploration plans for so-called frontier areas (i.e. hardly explored). In case of geological–geophysical mapping, it offers procession and interpretation services, and in case of seismic, magneto telluric, gravity and magnetic methods it can provide field acquisition with wide references. There is a sediment geological and geochemical laboratory in the building at Stefánia road. Typical areas of service: re-procession and re-interpretation of archived data based on modern equipment park.

MBFSZ professional libraries

The collection of the Geological and Geophysical Libraries embrace the total geological–geophysical documents and maps of the almost 150-year old state geological exploration for the then existing territory of Hungary.

In addition, its collection keeps on growing through exchanges, donations and purchase and new international contemporary and archive geological maps documents and publications are continuously collected.

The Geological Library since 1869, and the Geophysical Library have been providing services since 1922.

Science Direkt, Scopus and Springer Link databases are available in both Libraries through EISZ service.

Nearly 70% of the publications of the predecessor institutions are in full text available in the National Széchényi Library Electronic Periodicals Archive and Database (EPA) and through the database of the Hungarian Electronic Library (MEK).

The electronic catalogue and information on working hours, etc. are available on the website of the Survey. The Geological Library is located at Stefánia road 14., whereas the Geophysical Library at Columbus street 17–23.

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Glossary

abrasion: one type of mechanic fragmentation when grains erode each other and the surrounding environment.

acid stimulation: injection of acidic fluid into the reservoir rock (limestone, dolomite, sandstone, etc.) to enlarge pore volume and permeability.

adhesive water: water in reservoir rocks, retained in the rock grain, if any other fluid (crude oil, natural gas) displaces the mobile water. This water is absorbed in the rock grain, so it cannot be expelled by crude oil and natural gas.

agglomerate: a coarse-grained pyroclastic rock composed of angular rock fragments predominantly larger than 64 mm in a matrix of volcanic ash; typically occurs in volcanic vents.

Alcapa Mega-unit: large structural mega-unit built up of several structural units forming the north-western part of the pre-Cenozoic basement of the Carpathian Basin. Alcapa is an acronym of the initial letters of Alps, Carpathians and the Pannonian Basin.

alginite: sedimentary rock made up of fossil algae and weathered volcanic material.

allochthon: rock units, sediments or fossils that moved large distances from their original locations. Its opposite is autochthon.

alluvium: the area of unconsolidated detrital material deposited by a stream. It consists of clay, silt, organic material, sand and gravel.

Alpine orogeny: a tectogenetic phase (opening of oceans, deposition of oceanic sediments, closing of oceans, collision of continental plates, orogeny and uplifting) in the Mesozoic and Cenozoic Eras ranging from the end-Triassic (circa 200 Ma) until the end of the Pliocene (circa 2.6 Ma). It was triggered by the collision of the African and European plates. As a consequence of this tectogenetic series, the Alps and the Carpathians were uplifted and the Carpathian Basin was developed.

Alpine Tethys: a narrow oceanic branch split up when the Atlantic Ocean was formed; it existed during the Jurassic and Early Cretaceous.

amphibole: mineral group belonging to chain silicates, often occurs both in magmatic and metamorphic rocks.

anchimetamorphic: very low-grade metamorphism, as the original material, texture and structure of the protolite can be still recognised (e.g. metasandstone, metavolcanic rock, etc.)

andesite: igneous rock with neutral composition (with 52–66% silicon dioxide content) – named after the Andes Mountains in South America.

angular unconformity (angular discordance): when rocks above and below their contact have different orientations; forms due to tectonics.

anhydrite: calcium-sulphate mineral, mass-like, grainy or rough crystalline, colourless, reddish-grey or pink, with perfect cleavage, a gypsum version with no crystalline water.

anoxic: marine or lacustrine environment characterised by very low volume of dissolved oxygen.

anticline: a type of fold in which the oldest formations are in the core.

appraisal: delineates depth, extension of hydrocarbon fields and reservoirs discovered during the exploration phase; clarification of petrophysical and hydrodynamic parameters and contacts of the reservoirs.

arkose: sandstone containing more than 25% feldspar.

asphalt: brownish-blackish solid or semi-solid bitumen material, which can be found in nature, or produced from crude oil distillation (refining) as a residue. It melts at 150–200 °C temperature.

asphaltite: 1. hydrocarbon complex in dark colour, solid, hard to melt, naturally occurring. It is insoluble in water, but more-or-less soluble in benzene; 2. One of the hardest solid hydrocarbon compounds (gilsonite, grahamite).

asthenosphere: the lower, ductile zone of the Earth's upper mantle, on top of which the lithospheric plates move ("float").

Austro Alpine nappe system: nappe system of the Eastern Alps.

autochthonous: 1. rocks that remained in place after their formation; 2. sequence of beds that did not move from the place of formation despite robust folding or fragmentation by faults; 3. fauna, flora that were fossilised at their original habitat, and suffered no dislocation. Its opposite is allochthonous.

Badenian: an age of the Middle Miocene between 16.0–12.8 million years old (named after the city Baden in Austria).

Balaton Line: one of the main structural zones in the Carpathian Basin, forming the boundary of the Alcapa Mega-Unit at SE towards the Mid Hungarian Shear Zone (or Sava Zone).

Barremian: an age of the Early Cretaceous (circa 131–125 million years ago).

basalt: igneous rock with less than 52% silicon-dioxide content); its greyish-black colour comes from the dark-coloured mineral grains (pyroxene, amphibole) and it has a microcrystalline, glassy texture.

basement: bottom formations of a sedimentary basin; a complex, usually of igneous and metamorphic rocks, that is overlain unconformable by sedimentary strata. Also known as basement rock.

basin analysis: method of modelling to understand the conditions of a sedimentary basin from aspects of stratigraphy, facies, structural, geological evolutionary history, hydrocarbon generation, migration and accumulation.

basin inversion: elevation temporarily or finally replacing the subduction during the evolution of structural basins, which is driven by compression tectonics.

basin: sedimentary region of the Earth formed by long-term subsidence, creating accommodation space for infilling by sediments.

bathyal: deep marine depth, below the shelf edge between 200–3,000 m.

bentonite: rock with high clay mineral content originated from eroded volcanic tuff. Its main mineral is montmorillonite.

Berriasian: the first Age of the Cretaceous period (circa 145–139 million years ago).

bioclasts: fossils and fossil fragments in sediments or sedimentary rocks.

biogenic rock: sedimentary rock containing fossils in rock-forming quantity.

bitumen: l. product of crude oil distillation, not occurring in nature. 2. general name of solid and semi-solid hydrocarbons as natural asphalt and tar sand. 3. organic compounds which are soluble in organic solvents.

blowout: A blowout is the uncontrolled release of crude oil and/or natural gas from an oil well or gas well after pressure control systems have failed.

bottom hole depth: 1. actual depth of a well; 2. total measured depth (TMD) or total vertical depth (TVD) of a well.

bottom-hole pressure: pressure in the bottom of the well, or at the tested or producing layer. Typical bottom hole pressure measurements: 1. dynamic pressure – at producing state; 2. static pressure – at closed wellhead.

breccia: rock composed of angular and subangular, randomly oriented clasts that suffered little transportation. Most breccias are of continental, less often of marine facies; marine breccias – composed of coarse-grained, angular rock fragments – were deposited next to the coastline. The matrix can be calcareous, siliciclastic, clayey, etc.

calcareous algae: type of algae that excretes calcium carbonate from seawater.

calcareous marl: sedimentary rock with 20–40% clay content, transitional between marl and limestone.

calcite: one of the most common calcium carbonate minerals in nature. Many forms of calcite crystals are known; they are excellent temperature indicators and present almost in every rock. Calcite is the most important grain and cement forming component of carbonate rocks. It is an important skeleton building material of living organisms that build a solid external skeleton.

Calpionella: extinct genus of single celled eukaryotes.

cap rock: seal rock. 1. a practically impermeable stratum, which is above the crude oil and natural gas reservoir, and prevents migration of hydrocarbon from the reservoir; 2. full sequence of beds located above the reservoir rock; 3. rock beds covering the mineral reservoirs.

carbon dioxide: stable compound made of carbon and oxygen in gaseous state (CO_2). Often accompanying hydrocarbon gases, but it occurs also in very high concentration (96–98%) forming a unique gas reservoir.

carbonate platform: a sedimentary environment characterised by an approximately plane surface which is covered with shallow marine water. It has a large areal extension (occasionally reaching some thousands of square kilometres). It is generally formed in connection with shelves, but it also has an island like variant which is encircled by deep sea. The great quantity of carbonates that make up the platform is derived from the activity of shallow-marine organisms (algae and higher plants, sponges, corals, bryozoans, molluscs, echinoderms, etc.). These organisms excrete calcium carbonate or trap it from the sea water. Conditions have been favourable for the formation of carbonate platforms in several periods of the Earth's history, such as the Triassic Period (during the course of the evolution of the Tethys Ocean). The Bahama Bank is an example of a recently formed carbonate shelf.

carbonate ramp: a shelf with very small (usually less than 1°) declination, characterised by carbonate sedimentation.

Carboniferous: period of the Palaeozoic era between 358.9 and 298.9 million years ago (named after the Latin name of carbon).

cementation: a diagenetic process, hardening and welding of clastic sediments (those formed from pre-existing rock fragments) by the precipitation of mineral matter in the pore spaces. Quartz, calcite, dolomite, siderite and iron oxide are the most general cementing materials.

Cenozoic: the most recent geological era of the Earth history, which began 66 million years ago and continues to the present?

Cerithium: genus of small to medium-sized marine gastropods in the family Cerithiidae.

chronostratigraphic unit: represents a well-defined stratigraphic interval of a certain geological age.

clay marl: argillaceous marl, a sedimentary rock composed of clay and 20–40% calcium carbonate.

clay: a fine-grained rock comprising clay minerals, rock clasts and organic matter. Diameter of rock grains is less than 0.002 mm. Grains are composed of clay minerals (montmorillonite, illite, kaolinite and other phyllosilicates), quartz, feldspar, mica or a splinter of a rock, grain of organic origin, and the binding material can be calcareous, silica, iron cement.

collision: plate tectonic collision of continents.

combined trap: a hydrocarbon trap that cannot be classified into a single structural, stratigraphic or lithologic type, where parameters of two or more types dominate together.

compaction: reduction in sediment volume due to compressive effects. Usually caused by the mass of younger sediments deposited onto sediments.

compressional tectonics: a structural movement accompanied by compression.

condensate: light liquid hydrocarbon usually located in gas reservoirs (propane, butane, pentane, hexane). Its colour changes from clear as water to light brown, with a viscosity between 739–779 kg/m^3. Predominantly found in gas condensate reservoirs, but it occurs also in natural gas and crude oil reservoirs.

conformity: sequence of beds with bedding and contacts parallel, and with no hiatus in deposition, contrary to unconformity.

conglomerate: clastic sedimentary rock dominantly made of pebbles.

consolidation: any or all processes where the loose, plastic or liquid rock material becomes a solid, compacted rock.

Corbula: a small-sized gastropod genus with convex shell, often found in young (Miocene) marine sediments in Hungary. These shells are frequently found in large masses (together with the fossils of the gastropod Turritella) in layers of Middle Miocene (Badenian) Szilágy Clay Marl Formation; thus this formation was formerly well-known as "Turritella–Corbula clay marl".

core (drilling core): rock sample taken during well drilling, using a core drill bit or sidewall coring tool. Cores are taken for analysing petrophysical, fluid content, lithology, fauna, and etc. features of the rock core.

core complex: isostatic elevation of the lower and middle continental crust at those parts where the orogenic nappe units slide down from the lower section of the crust due to extension along flat surfaces, thus leaving the units uncovered.

correlation: definition and identification of stratigraphic units located at different places based on their stratigraphic position. A correlation can be performed by different types of stratigraphy (litho-, bio-, chrono-, magneto- etc.).

Cretaceous: the last period of Mesozoic era, between 146–66 million years ago (named after the chalk of north-west Europe).

cross-bedding: frequent bedding type of sedimentary rocks, where strata or packages of strata are clearly separated by an angular unconformity. Based on its character and size, conclusions can be drawn regarding conditions of the palaeo-environment, e.g. flow velocity of the medium carrying the sediment grains, and the direction of flow.

crude oil: a brownish-black (with greenish shade) liquid (semi-solid) mixture occurring naturally and containing a relatively large quantity of volatile compounds, dominantly consisting of hydrocarbons. It usually also contains sulphur, nitrogen or oxygen components and trace elements. Crude oil may contain gas, or components in liquid or solid state depending upon the crude oil type (quality), pressure and temperature conditions. It is soluble in carbon tetra chloride, ether and benzene.

crystalline rock: collective noun referring to metamorphic and intrusive magmatic rocks.

cutting: rock clast samples, broken up and removed from the drilled rock by the drilling bit during drilling, and carried by the drilling fluid from the bottom hole to the surface.

dacite: fine grained (felsic) extrusive volcanic rock, intermediate in composition (with 63–69% silicon dioxide content) between andesite and rhyolite – named after the province of the Roman Empire, Dacia)

delta plain: fan-shaped flat area with shallow (2–5 m) water depth, with low slope, variable morphology, generated at the delta river estuaries at seas.

delta sediment: river transported sediments deposited in the delta areas of the lakes or seas. Characteristic feature is cross-bedding.

depression: 1. an area sunken below its surrounding; 2. pressure difference emerging within a pressure system (e.g. result of reservoir fluid pressure-drop driven by production).

diagenesis: 1. physical, chemical change following the deposition of sediments, formation of consolidated rock. Diagenetic effect: compaction, cementation, re-crystallisation; 2. rock formation process of sediment grains into solid rock.

diatexite: partially melted and re-crystallised metamorphic rock.

differential compaction: relative thickness change of clay and sand (or limestones) arising from their different compaction rate after burial due to reducing pore space.

discovered hydrocarbon resource: quantity of hydrocarbon which is estimated on a given date, to be contained in known accumulations. Reservoir test and geophysical logging prove the presence of hydrocarbons. These are sub-divided into commercial and non-commercial categories.

dislocation zone: area of the rock bodies within which larger rock blocks move apart from each other. Rocks within the zone might become significantly deformed in accordance with the type and size of the dislocation.

dissolved gas: natural gas dissolved in crude oil or water. In addition to the gas quantity available for dissolution, the fluid system pressure, temperature, and bubble point pressure determine the quantity of gas dissolved.

distal: situated away from the centre of the body or from the point of attachment. Dominantly containing finer grain size farther from the source of sediment.

dolomite: a rock made of calcium-magnesium-carbonate mineral.

dry gas: natural gas containing hydrocarbon gases with few carbon atoms. It usually has no contact with the oil body and contains less than 10–12 grams of liquid material per cubic meter.

dry well: a well with no hydrocarbon production.

eclogite: high grade metamorphic rock predominantly consisting of pyroxene and garnet.

edge water: where the water aquifer exclusively feeds one side or flank of the reservoir. The edge water fills up the pore volume of reservoir in zones below the water-hydrocarbon contact. The water may be in a moving or static state, and active or passive. Active flank water may have a significant role in depleting the reservoir.

effective porosity: ratio of the porosity of a rock available to contribute to fluid flow through the rock compared to total rock volume, expressed as a percentage.

effective thickness: total thickness of the reservoir, not considering the thickness of impermeable layers.

Eggenburgian: age within the Miocene epoch circa between 21.5–18.2 million years.

elevation above/below sea level (asl/bsl): vertical difference between elevation and given sea level (point of reference). When stratum/layer is identified, the reference is made to sea level and not to the topographic surface.

emulsion: dispersed systems with fine distribution, e.g. mixture of oil and water.

Eocene: epoch of the Palaeogene period between 56–33 million years ago (named after the Greek word: dawn).

epeirogenic movement: uplift or depression of lands exhibiting long wavelengths and little folding apart from broad undulations.

epicontinental: 1. shallow sea on the continental plate. 2. Sediment deposited in an epicontinental sea.

erosion: collective name for external forces and processes degrading and destroying the crust. Erosion may happen also due to water, ice, wind and human intervention (anthropogenic effect).

evaporite: salt rock (e.g. rock salt, gypsum, anhydrite).

exploration well: 1. well drilled for acquiring data of geological formations in larger areas (drilling to acquire rock parameters) or/and on structures, 2. well drilling to discover a hydrocarbon resource. It is called wildcat well in petroleum exploration.

exploration: the initial phase in petroleum operations that includes generation of a prospect, a play or both, and the drilling of an exploration well.

extensional tectonics: tectonic processes associated with stretching of the earth crust or lithosphere.

external forces: collective noun for forces destroying the earth crust surface by wind, water and ice.

facies: general external appearance (lithological, palaeontological, etc. characteristics) of rocks, referring to the circumstances of their formation.

fault: a fracture in rock along which the adjacent rock surfaces are differentially displaced.

field (hydrocarbon): an area where a group of crude oil and/or natural gas reservoirs are connected geologically.

fluid pressure: the pressure characterising the fluid in the rock. Reservoir pressure, formation pressure, rock pressure can be also used as synonym names.

fluid: mixture contained within the hydrocarbon reservoir which are situated in the reservoir rock. Reservoir fluids normally include liquid hydrocarbon (mainly crude oil), aqueous solutions with dissolved salt, hydrocarbon and non-hydrocarbon gases such as methane and carbon dioxide, nitrogen, hydrogen sulphide respectively.

flysch: graded sequence of deep-marine siliciclastic sediments. It is made of fining upward cycles built of sandstone–silt– and clay layers.

fold: structure of rock strata of originally flat and planar surfaces that are bent or curved as a result of ductile deformation.

foraminifera: single-celled marine animals that build calcareous or siliciclastic grain skeletons of very variable form, size and composition. Certain groups are useful for the biostratigraphic subdivision of sedimentary rocks.

foreland basin: a basin developed parallel with mountain range that have orogene belts, and created by gravity driven crustal thickening that causes the lithosphere to bend.

formation: base unit of lithostratigraphic classification, it can be identified from its environment using petrophysical methods, and can be shown on geologic maps. Its smaller units are called members and beds.

fossil: petrified remnant of living organism.

free gas reservoir: a reservoir with gas or gas condensate content and no crude oil.

freshwater: water with less than 0.02% salt content.

gas cap: free gas volume located in a saturated (gas cap-type) crude oil reservoir above the oil body. The reservoir contains more natural gas that can be dissolved in crude oil at given reservoir pressure, temperature, and chemical parameters.

gas condensate reservoir: a hydrocarbon reservoir where in addition to gas, liquid hydrocarbon (condensate) is also present (under normal conditions). The viscosity of liquid produced with gas can be between 0.739–0.779 g/cm^3, while the gas–liquid ratio is 1,424–12,460 m^3/m^3 (relative to dew point).

gas (cap) drive reservoir: a primary recovery mechanism for oil wells containing dissolved and free gas, whereby the energy of the expanding gas is used to drive the oil from the reservoir formation into the wellbore.

gas hydrate: grainy material in solid state, similar to snow or ice, containing 1 molecule methane, ethane, propane or butane and 6 or 7 molecules of water. It is generated in permafrost areas, at the bottom of deep seas, or oceans under high pressure and low temperature. It may be formed also inside gas pipelines, causing plugs or occlusion or blockage.

gas saturation: 1. part of total rock porosity that is filled up with gas (expressed as a percentage), 2. gas dissolved in crude oil.

gas well: a producing well which produces mainly gas.

gas–oil contact (GOC): natural gas and crude oil contact.

gas–oil ratio (GOR): ratio of the jointly lifted natural gas and crude oil quantities relative to each other, expressed in m^3/m^3.

gas–water contact (GWC): contact of natural gas and bottom/edge water.

geological exploration: technical–scientific operation accompanied by an excavating of the ground surface, performed by applying geophysical and geochemical methods. Its aim is to acquire information on raw material, structural and evolution history parameters of the crust.

geological log: profile presenting the vertical cross-section of part of the crust in a specific direction. Geological and/or geophysical data are used for the editing work.

geological model: a synthetic representation of geological observations made on and below the Earth surface.

geology: a natural science for studying the Earth, the materials of which it is made, the processes that act on these materials, the products formed thereby, and the history of the planet and its life forms since its origin.

geophysics: a natural science describing the physical phenomena and associated measurable physical parameters which occur inside and on the Earth (and — in a wider sense — inside all planets).

geostatic pressure (lithostatic pressure): pressure exercised by a rock column (sequence of beds) driven by gravity.

geothermal gradient: version of the temperature gradient extrapolated onto the Earth (dT/dh). It changes from location to location.

glacial: 1. made by ice, 2. ice age or icy period.

glauconite: green mica with high iron, aluminium and magnesium content, often found in marine sediments.

gneiss: crystalline rock generated during middle to high grade metamorphism of igneous or sedimentary rocks.

granite: intrusive magmatic rock with 66–70% silicon dioxide content.

Hauterivian: an age of the Early Cretaceous epoch, circa 134–131 million years ago.

hemipelagic: part of open deep marine environment located near the seashore. Fine-grained clastic material is transported from onshore.

Holocene: last epoch of the Earth history, lasting nearly 12,000 years.

hydrocarbon exploration: process of finding and measuring underground hydrocarbon accumulation; applies highly sophisticated technology to detect and determine the extent of hydrocarbon, using exploration geology, geophysics and drilling.

hydrocarbon gas: a material in gaseous state under normal pressure and temperature containing carbon and hydrogen compounds. The most common form is methane, often accompanied by hydrocarbons with a higher number of carbon atoms.

hydrocarbon geology (petroleum geology): a science focusing on the geological aspects of the elements and processes of the hydrocarbon systems, and the exploration and production of crude oil and natural gas.

hydrocarbons initially in-place (HIIP): total (recoverable and non-recoverable) quantity of hydrocarbon originally found on the ground's surface or undersurface in conventional and unconventional accumulations, including the exploited, the discovered and the undiscovered (prospective) resources.

hydrocarbon reserve: discovered, commercially recoverable hydrocarbon quantity. A reserve can be in production, developed for production or undeveloped. According to the uncertainty involved in estimation of reserve categories are proved, probable and possible applied.

hydrocarbon resource: discovered or undiscovered hydrocarbon quantities which may or may not be produced in the future.

hydrocarbons: 1. compounds that contain only carbon and hydrogen atoms, 2. collective name of crude oil, natural gas and gas condensate.

hydrostatic pressure: pressure of homogenous liquid in gravity space, calculated in "h" depth below subsurface. If the pressure on the surface of liquid with "r" density is "p_o", then the pressure at depth "h" is $p = p_o + \rho g h$ (g = standard acceleration due to gravity). The pressure rate is caused by the water column (with density and temperature under normal conditions) between the tested point of the reservoir and the piezometric surface.

igneous rocks: rocks formed by direct crystallisation of magma.

impermeable rock: rock with texture that is practically impermeable to water. Among sedimentary rocks primarily clays and marls are impermeable, thus they have outstanding significance in the formation of the hydrocarbon cap rocks (seals) and traps.

inert gas: gas which is not involved in any chemical reaction (the noble gases He, Ne, Ar, Kr, Xe, and Rn). In the petroleum industry, in practical terms, a hydrocarbon gas is regarded as having inert content if the total volume of CO_2 and N_2 in the gas is over 5–8%.

intermediate oil: during atmospheric distillation (at temperature 250–275 °C) the density of key fraction is in the range of 825.0–860.2 kg/m^3.

intrusion: penetration of magma into the solid rocks.

isostatic: state of gravitational balance between the lithosphere and mantle.

Jurassic: the middle period of the Mesozoic era, between 200–146 million years ago (named after the Jura Mountain in Switzerland).

juvenile gas: gas associated with magmatic activity.

Karpatian: a regional age in the Miocene epoch between approximately 17.4–16.0 million years.

karstic: a limestone area (plateau), with typical holes, caverns, caves dissolved by water, with frequent subsurface streams or lakes, named after Karst of Dinarides (from Slovenia to Albania).

kerogen: complex, fossilised organic material present in sedimentary rocks, especially in shales, the residue in the rocks after extraction using chloroform. It is insoluble in normal organic solvents and does not have a specific chemical formula. Upon heating, kerogen converts in part to liquid and gaseous hydrocarbons. Crude oil and natural gas are formed from kerogen. Based on its origin, kerogen may be classified as algal, mixed terrestrial or marine.

Kimmeria: a micro-continent that existed during the Triassic and Jurassic period.

large foraminifera: single celled animal that can be easily seen with naked eye, size up to 10–12 cm. It has solid, porous and calcareous skeleton.

lateral migration: migration of crude oil and/or natural gas in permeable rocks in lateral direction, along bedding or unconformity surfaces.

lean gas: dry gas; natural gas that contains few or no liquefiable liquid hydrocarbons.

lignite: brown coal with low calorific value, also containing wood, plant and soil remnants as a consequence of low carbonisation.

limestone: dominantly made of calcium carbonate ($CaCO_3$). In most cases it is not fully pure as it contains clay, dolomite, bitumen, graphite, carbon etc.

listric fault: a fault with a gradually flattening angle and a surface bent in the direction of its depth.

lithologic traps: a group of stratigraphic traps, continuity and permeability of the reservoir is terminated for migration direction due to change in lithology.

lithology: physical and mineralogical parameters of a rock.

lithostatic pressure: pressure or stress imposed on a reservoir by the weight of overlying material.

lithostratigraphic unit: group of rocks with similar petrological characteristics.

lithostratigraphy: 1. stratigraphy of rocks based on petrological features; 2. recognition and identification of physical parameters of sedimentary rocks.

lithothamnium: calcareous red algae.

Lombardia: extinct planktic crionoid group from the Late Jurassic and Early Cretaceous.

low grade metamorphism: takes place at low pressure (300–600 MPa) and low temperature (200–320 °C)

magma: a mixture of molten or semi-molten rocks, volatiles and solids, found beneath the surface of the Earth.

Magura Ocean: part of the Western Tethys which closed from the end of the Eocene and terminated at the middle of Miocene.

marker horizon: stratum (rock bed) with regional extension that can be easily identified by its physical parameters, and "can be easily monitored" with geophysical or geological methods.

marl: sedimentary rock with mixed composition, containing 40–60% clay and carbonate, it represents a continuous transition between limestone (dolomite) and clay.

marsh gas: swamp gas, bog gas, contemporary biogenic methane formation. It does not contain any hydrocarbon with more than one carbon atom. Presence of carbon dioxide, nitrogen and hydrogen sulphide is typical. Frequently occurs in peat areas.

matrix: the finer-grained groundmass and cementing material wherein larger grains, crystals or clasts are embedded.

Meliata–Vardar Ocean: southern branches of Mesozoic Neotethys Ocean.

Mesozoic era: era of the Earth history between 251 and 66 million years ago. Its three periods are: the Triassic (251–200 million years ago), Jurassic (200–146 million years ago) and Cretaceous (146–66 million years ago).

metamorphic rocks: rocks that have suffered metamorphism under high pressure and/or temperature. During metamorphism the mineral composition and texture of the original rock change while the chemical composition remains the same. The emerging new mineral forms are characteristic of pressure and temperature conditions.

methane hydrate: gas hydrate.

migration (hydrocarbon migration): movement of hydrocarbon from source rock toward a reservoir, or seepage across the pores and fractures of rocks. In general it means movement of fluids by diffusion and movement of elements within the crust.

mineral raw material: a mineral material that can be utilized at the existing level of scientific-technical development. Soil and water (irrespective of state) are not considered mineral raw materials.

mineral resource: those mineral materials whose quantity and quality is defined by geological and mining technology and by economic parameters through estimates or calculations.

mineral: a material of natural origin, with relatively constant composition and regular structure easily described with a formula. It is crystalline or amorphous.

Miocene: an epoch of the Cenozoic era between 23.0–5.3 million years ago.

mixed base crude oil: where both paraffins and naphthenes are present, as well as aromatic hydrocarbons.

molasse: clastic sediment (sandstone, shale, and conglomerate) sequence deposited during the last phase of an orogenic cycle. These sediments are typically the non-marine alluvial and fluvial sediments of lowlands, as compared to deep-water flysch sediments.

Mollusc: a useful animal phylum from the geological aspect, it includes gastropods (Gastropods), shells (Bivalve) and cuttlefish (Cephalopoda). Each is an excellent environment indicator (marker) and some can be used for purposes of stratigraphy.

mud loss: drilling mud penetrates into layers around the borehole, circulation of the mud is partial. Mud loss is expressed as a percentage, relative to the total mud injected into the well.

nannoplankton: living, floating organisms of microscopic size.

naphthene-based crude oil: during atmospheric distillation of crude oil the density of the key fraction (between 250–275 °C) is higher than 860.2 kg/m^3.

nappe: large sheet-like rock unit that has been moved more than 2 km above a thrust fault from its original position.

natural gas: l. material occurring in a gaseous state at normal temperature and pressure (15 °C and 1 bar). It consists of light paraffinic hydrocarbons (mainly CH_4), carbon dioxide (CO_2), and nitrogen (N_2), eventually containing hydrogen sulphide (H_2S) and noble gases; 2. any material occurring in a gaseous state in nature.

natural gas reservoir: gas volume accumulated in a hydrocarbon reservoir (free gas, cap gas or dissolved gas).

Neogene: period in the Cenozoic era between 23 and 2.6 million years ago, including the Miocene (23–5.3 million years ago) and Pliocene (5.3–2.6 million years ago) epochs.

Neotethys: equatorial ocean between the African and Eurasian plates, that developed rifts in the Middle Permian and closed during the Palaeogene.

neritic: zone of seas and oceans under the low tide level, down to 200 m water depth.

Nummulites: one of the representatives of large foraminifera with up to 10–12 cm in diameter. Nummulites used to live in large populations in the sub-tropical warm shallow seas during the Palaeogene. It was the most important marker fossil of the Eocene epoch. Its shape was similar to a coin, so it is also referred to as “the coins of St. Ladislaus” in Hungarian legends.

oil reservoir with gas cap: oversaturated/saturated crude oil where the total gas volume cannot dissolve in the oil and so accumulates above the oil, forming a “cap”.

oil saturation: portion of the total effective rock porosity (pore volume) filled up with crude oil, expressed as a percentage.

oil shale: shale rock, containing an amount of thermally unmatured organic matter (kerogen), such that extraction can be commercial by distillation.

Oligocene: the youngest epoch of the Palaeogene period between 34–23 million years ago.

ooid: sediment grain with maximum 0.2–2 mm diameter. It has a concentric structure made of calcium carbonate separated chemically from strongly moving seawater (e.g. due to excessive waves) and developed around carbonate or clastic central grains.

open hole section: a section of a well without casing. The wall of the borehole rocks is drilled through.

orogeny: a phase of plate tectonic cycles when the rock sequence folded and thickened in the subduction zone and emerged isostatically.

Ottnangian: a regional age of the Miocene epoch between 18.2–17.4 million years ago.

overpressure: fluid pressure higher than the hydrostatic pressure in a reservoir.

Palaeocene: the earliest epoch of the Palaeogene period between 66 and 56 million years ago.

Palaeogene: first period of the Cenozoic era between 66 and 23 million years ago. Its epochs are the Palaeocene (66–56 million years ago), Eocene (56–34 million years ago) and Oligocene (34–23 million years ago).

palaeosoil (fossil soil): ancient soil layer creating the palaeo-surface. It is mainly brown, reddish-brown or red, originally with high persistent humus containing a fossilised former soil layer.

Palaeotethys: the pre-Mesozoic Tethys Ocean that existed during the Palaeozoic and the Triassic, and closed during the Jurassic.

Palaeozoic: an era of the Earth history, covering the time interval between 542–251 million years ago. Its periods are: Cambrium, Ordovician, Silurian, Devonian, Carboniferous and Permian.

Pannonian Lake (Lake Pannon): a lake that filled the Pannonian Basin between 12–5 million years ago with variable extension, depth and salt content. It was gradually filled up with sediments from deltas of rivers arising mainly from north-west, pushing the open water section of the lake towards SE (named after the Latin name of the Roman province of Transdanubia, Pannonia).

paraffin hydrocarbon (alkane): white, odourless, tasteless and chemically inert water-like material of hydrocarbons in crude oil. It has a saturated hydrocarbon chain structure, with a general formula C_nH_{2n+2}. Paraffins are major constituents of natural gas and petroleum. Paraffins containing fewer than 5 carbon atoms per molecule are usually gaseous at normal (room) temperature, those having 5 to 15 carbon atoms are usually liquids, and the straight-chain paraffins having more than 15 carbon atoms per molecule are solids.

paraffin-based crude oil: crude oil containing paraffin wax in solution. The oil has relatively high hydrogen content, whereas its carbon content is relatively low. In case of atmospheric distillation the density of the key fraction at 250–275 °C is lower than 821 kg/m^3.

Paratethys: an E–W oriented sea branch evolved in the northern foreland of the Alpine orogene belt during the Palaeogene.

pelagic: vast areas of open seas and oceans far from the coastline.

pelite: fine-grained, clayey sedimentary rock.

Penninic Ocean, Penninic structural unit: one of the northern branch of the Atlantic Ocean, which opened at the end of the Triassic and closed during the Cretaceous. The West Alpine Penninic structural unit is built up of its sediments, and its metamorphic formations exposed on surface only in tectonic windows in the Eastern Alps (e.g. in the Kőszeg Mountains).

Periadriatic line: a dominant structural zone of the Alps which separates the Southern Alps (nappes moved towards South) from the Northern and Eastern Alps (nappes moved towards North).

periglacial: an area next to onshore ice sheet.

permeability: measure of the ability of rocks to transmit fluids. Its rate depends on the size, form and connection of rock pores. Movement of fluids with constant viscosity within a given distance and during a determined time interval will determine its value.

permeable rock: a rock with texture that lets fluids flow through due to pressure difference. Pores with capillary or sub-capillary size among the grains can also ensure the permeability.

Permian: the youngest period of the Palaeozoic Era between 299–251 million years ago.

petroleum geology: hydrocarbon geology.

petrology: lithology, a science focusing onto natural conditions, characteristics and history of rocks.

phase contact: 1. contact among water, crude oil or natural gas, and natural gas and crude oil in the reservoir. Ideally it is horizontally flat, practically an oblique surface due to lithology or fluid flow. Contacts may generally reach each other in a transitory zone having the thickness of a few tenths of a metre or several metres, where the ratio of the relevant fluids vary; 2. surface of contact for heterogeneous systems. Here the parameters of the material are transitory, and they vary according to parameters of both phases.

phyllite: foliated metamorphic rock. It is primarily composed of fine-grained quartz, sericite mica, and chlorite.

picrite: volcanic rock, containing less than 45% silicon dioxide and high iron and magnesium content, rich in dark minerals (e.g. pyroxene).

Pleistocene: the older epoch of the Quaternary period, between 2.6 million and 12,000 years ago.

Pliocene: the younger epoch of the Neogene period, between 5.3 and 2.6 million years ago.

point bar: a depositional feature made up of alluvial sediments accumulated on the inside bend of streams and rivers.

polymetamorphism: the presence of more than one phase of metamorphism.

porosity (pore volume): ratio of rock total pore volume versus total rock volume, usually expressed as a percentage.

post-rift sedimentation: sedimentation after rifting. Rock units represent extension in the Pannonian Basin, as well as the filling-up and thermal consolidation of partial basins that occurred in different times in each sub-basin from the Sarmatian stage onward.

pre-Alpine: prior to the Alpine tectonic cycle.

pre-Cenozoic: formations older than Cenozoic (66 million years).

pre-rift: prior to rifting.

pressure gradient: differential quotient of pressure and depth, dp/dh.

primary migration: expulsion of hydrocarbons from the source rock into permeable rock. Primary migration of crude oil occurs in water, gas or liquid-hydrocarbon phase.

primary porosity: the porosity connected to rock formation (genetics) preserved from deposition through lithification.

producing well: a well drilled to produce hydrocarbons. The number of wells and drilling locations are specified in the field development plan.

prospective resource (hydrocarbon): quantity of the undiscovered hydrocarbons in-place. Hydrocarbon resource that can be presumably discovered and extracted in the future based on geological assumptions and indirect geological information (prognostic resource).

progradation: dislocation of coastline towards the basin, when the degree of sediment accumulation is higher than the growth degree of available space.

pseudoanticline: anticline formation created by sediments compaction. Sediment thickness at the hinge zone and flanks of anticline is different, so compaction on the flanks is more pronounced compared with the anticline hinge point. Under the hinge zone of anticline there is an elevated basement or buried hill.

pyroclastics: volcanic deposits, developed during volcanic explosions. Their classification is based on grain size, similarly to siliciclastic sediments.

quartz: a silicon dioxide (SiO_2) mineral with characteristic pyramid-like crystalline structure, and extreme hardness. One of the most important rock-forming minerals, it may be generated in all main magmatic crystallization phases, but could also be the product of hydrothermal and metamorphic processes. It is one of the most important rock-forming mineral of siliciclastic sediments.

Quaternary: the last period of the Earth history, i.e. the last 2.6 million years, divided into Pleistocene (2.6–0.01 million years) and Holocene (the last 12,000 years).

radiolarite: sedimentary rock generated from skeletons of radiolarians (marine plankton group with silica skeleton).

radiometric age: “absolute” age calculated from quantity of isotopes of radioactive elements in the rocks.

recent: younger than Pleistocene. A distinguishing marker of living organisms, formations and phenomena of the present age.

recoverable hydrocarbon resource: hydrocarbon volume that is most presumably recoverable from the discovered or not yet discovered reservoirs.

recovered hydrocarbon resource (production): that part of the hydrocarbon initially in-place that was produced until a given date. The total produced volume is the hydrocarbon volume produced from a reservoir until a given date. The annual production is the volume produced from the annual starting date until the end of the year.

reef limestone: biogenic limestone produced by reef-building organisms (corals, bivalves, sponges, bryozoans etc.).

regression: retreat of the sea from the shore due to onshore elevation or/and fall of sea level. Negative shore displacement.

reservoir (hydrocarbon): formation (rock) saturated with crude oil and/or natural gas which belongs to a consistent pressure system. It has the following types: natural gas reservoir, gas condensate reservoir, unsaturated crude oil reservoir, saturated crude oil reservoir (oil reservoir with gas cap).

reservoir content: fluid located in rock pore volume.

reservoir pressure: fluid pressure in the reservoir.

reservoir rock: rock formed in natural environment and having porosity suitable for accumulating fluids. Part of a reservoir saturated with hydrocarbon (crude oil, natural gas). Best and most common reservoir rocks are: sand, sandstone, gravel/pebble, conglomerate, breccia, limestone, and dolomite.

reservoir space: effective porosity, where the fluid is able to move.

residual resource (hydrocarbon): The quantity of hydrocarbon that cannot be economically recovered from the reservoir using the available and applicable technology (see unrecoverable resource).

retrograde metamorphism: metamorphic process of lower degree that overprints the originally higher grade metamorphic rocks.

rhyolite: light coloured extrusive igneous rock with high silica content (>69 wt% SiO_2) containing also quartz. It is the extrusive equivalent of granite.

rift: a linear zone where the lithosphere is being pulled apart.

rudists: a group of heterodont reef-building bivalves with thick, horn-shaped valves, which lived in shallow marine environments during the Late Jurassic and the Cretaceous.

sand: loose sedimentary rock with grain size between 0.063 mm and 2 mm, where the quantity of grains within the given range of size is more than 50%.

sandstone: sedimentary rock of solid, compacted sand. More than 50% of it is sand-sized grains, matrix, and cement. Quartz is the most common of the sand grains. Matrix or cement can be calcite, dolomite, opal, chalcedony, quartz, limonite, etc.

sapropel: wet mud or sludge, rich in organic materials.

Sarmatian: age of the Miocene epoch 11.6–12.8 million years ago (named after ancient tribes living on steppes north of the Black Sea).

saturated crude oil: at a given pressure and temperature the crude oil saturated with gas is unable to dissolve more gas. Its pressure is lower than the bubble point pressure.

saturation: the quantity or degree of oil, gas and water in rock pores. It is usually expressed as the percentage of the total pore space or total porosity.

schist: crystalline rock with large, flat and sheet-like oriented grains developed during medium-grade metamorphism.

secondary migration: migration of hydrocarbons in permeable rocks (carrier bed, migration path) after expulsion to a trap.

secondary porosity: pore volume of rocks developed after diagenesis. It is generated by dissolving and corroding fracture systems in carbonate rocks, fractures of clay marls due to water loss and thermal effects, mineral re-crystallisation and mechanic effects.

section: l. cross-section in geology, 2. geophysical log representation of geophysical acquisitions performed in the borehole.

sediment: deposited solid minerals, rock fragments or organic materials; transported by water, air, ice and gravity from the place of origin to the place of deposition.

sedimentary basin: sunken area, where sediments accumulate.

sedimentary gap: lack of sediment deposition or erosion of sediment within the sequence.

sedimentary rock: rock formed by accumulation of sediments and cemented via diagenesis. Sediments contain grains of various sizes, fossils of plants and animals, products of precipitation from solution, or mixtures of them. Several sediments also contain volcanic ashes. Bedding is typical for sedimentary rocks, which is horizontal or near horizontal at deposition. Phases of sedimentation: weathering, erosion, transportation, deposition, diagenesis.

seismic time section: seismic section acquired by generating acoustic waves during seismic geophysical exploration jobs and registering the reflected waves by geophones. It provides information on location of sub-surface strata, layers and rock bodies, as well as on underground structural conditions.

Senonian: collective (not official) name of the last four stages of Late Cretaceous epoch (Coniacian, Santonian, Campanian and Maastrichtian)

sequence boundary: unconformity surface separating sediment units having interface with genetic and chronostratigraphic connection.

sequence of beds: layers with various age and characteristics e.g. crossed during drilling.

shale gas: natural gas that can be extracted from shale rocks applying unconventional methods (e.g. reservoir fracturing).

shale oil: crude oil and condensate that can be extracted from shales, marls applying unconventional methods.

shelf (continental shelf): gentle slope of the continents covered by less than 200 m shallow sea waters.

silt: sediment with grain-size between sand and clay, between 0.002 mm and 0.063 mm.

siltstone: lithified silt.

slate: a fine-grained, foliated, homogeneous metamorphic rock derived from fine grained sedimentary rock through low-grade regional metamorphism.

sour gas: natural gas with high hydrogen sulphide content. The H_2S content exceeds 0.1–0.2%.

source rock: rock deposited with organic materials. It is the rock from which hydrocarbon has been generated and from which the hydrocarbon was expelled during the primary migration. Under appropriate physical and chemical conditions all sedimentary rocks may become hydrocarbon source rock, but under identical conditions the shale, marl sediments are the best.

static pressure: pressure is generated in the well or in a closed wellhead by the fluid pressure in the layer when the flow of the layer content into the well disappears due to the fluid pressure in the borehole. Static pressure measured in reservoir depth or at well head is an important technical data.

strata identification: correlation.

stratigraphic trap: continuity of the reservoir is discontinued in the direction of migration because of stratigraphic change, any further connection becoming impermeable.

stratigraphy: part of geological sciences that study 3-D spatial and temporal relationships among rock units.

stratovolcano: volcanic structure built from a variable sequence of volcanic clast and lava flows.

stratum: rock layer made of various types rock, the smallest unit of the so-called sequence. It can be more or less clearly defined, and separable from the rocks above it and below it, or from its surroundings.

strike-slip fault: dislocation when the direction of various rock blocks is close to horizontal (throw is lower than 45°). Displacement can be sinistral (left moving) or dextral (right moving).

structural trap: a type of hydrocarbon trap that forms as a result of changes in the structure of the subsurface, due to tectonic, diapiric, gravitational and compactional processes.

subduction: plate tectonic process where convergent plates collide and the oceanic plate with higher density subducts below the continental plate with lower density.

sublittoral: a zone under low tide level with poor light. Located between the coastline and open water, water depth is 35–40 m to 80–100 m.

subvolcanic rocks: magmatic rocks trapped and crystallised near to the surface.

suture: closure of the ancient oceans, with typical rock types representative of oceanic basement remnants.

sweet gas: natural gas containing low hydrogen sulphide volume. The H_2S content is lower than 0.1–0.2%.

syncline: a folded structure where younger formation can be found towards its axis.

syn-rift sedimentation: sediment deposition along rift development. In the Pannonian Basin local sub-basins evolved due to extension and sediment accumulation in the Middle Miocene.

tar sand (oil sand): mixture of variable quantity asphalt and loose sand, which occurs in nature. Processing tar sand can produce more than 10% bitumen.

tectonic structure: general name of deformations (fractures, folds, ductile deformations) generated by internal forces of the Earth.

tectonic window: patch-like appearance of an underlying rock body which is covered by relocated rock unit (nappe).

terrenum: crust block, a unit with independent geological history.

terrigenous: terrestrial origin.

tertiary migration: re-accumulation of formerly evolved hydrocarbon reservoirs, further migration of hydrocarbons as a result of geological processes (i.e., faults).

Tethys Ocean: a gigantic ocean that existed during the Mesozoic era between Laurasia and Gondwana supercontinents along the Equator. At different times it split up into several minor oceanic branches.

texture: geometric aspects of rock components including size, shape and distribution. It is characteristic of the processes of rock formation.

tight sandstone gas (tight gas): natural gas recoverable using unconventional methods from sandstone with poor permeability.

Tisza Mega-unit (Tisia): a tectonic unit (microplate) forming the SE part of the basement of the Carpathian Basin.

total organic carbon content (TOC): total organic carbon content found in an organic compound compared to the weight of the rock volume, expressed in weight percentage.

trachybasalt: igneous rock with a composition between trachyte and basalt with 45 to 52% SiO_2 and with high alkali content (5 to 7% $Na_2O + K_2O$) content, consisting mainly of calcic plagioclase, sanidine, augite and olivine.

trachyte: igneous rock rich in alkali feldspar (orthoclase) with 57 to 69 % SiO_2 content.

transfer fault: a vertical or subvertical fault which, via dip-slip and strike-slip movements, allows the juxtaposition of two fault zones which have different displacement characteristics.

transgression: expansion of shallow sea, resulting in the progressive submergence of land, as when sea level rises or land subsides.

trap type: geological characteristic of a trap, which is used for defining the trap category. Types: 1. structural; 2. lithologic; 3. stratigraphic; 4. combined.

trap: a part of the hydrocarbon reservoir rock from which the hydrocarbon cannot migrate. This usually assumes a folded or tectonic form, porosity and permeability change in the reservoirs closed with impermeable top rock.

Triassic: the earliest period of the Mesozoic era between 251–200 million years ago (named after the characteristic triple division of sequence of beds in the German Basin).

tuff: sedimentary rock created by volcanic eruption, deposition of volcanic dust and fragments.

tuffite: sedimentary rock consists of 25–75% clastics of volcanic origin.

turbidite: clastic sediment transported by density flow and deposited on the bottom of the delta slope.

unconform (strata): deposition of rock bodies along different angles, broken up with eroded surfaces (opposite: conform).

unconventional (non-conventional) hydrocarbons: hydrocarbons that can be recovered from rocks only with special production and/or extraction methods (reservoir fracturing, pyrolysis, etc.).

underground blowout: displacement of hydrocarbon reservoir content into another reservoir rock with no control.

unrecoverable resource: difference between hydrocarbon in-place and recoverable resources.

unsaturated or undersaturated crude oil: at the given pressure and temperature more natural gas could be dissolved in oil. Its pressure is higher than the bubble point pressure.

Valanginian: an age of the Cretaceous period between 139–134 million years ago.

Variscan orogeny: orogenic phase of the Variscan tectontic cycle lasted from the Devonian until the end of the Permian.

vertical migration: migration of crude oil and/or natural gas vertically following bedding planes. It takes place through faults, fractures and other geological features.

viscosity: the viscosity of a fluid is the measure of its resistance to gradual deformation by shear stress or tensile stress. The unit of dynamic viscosity is Pascal second. The unit of kinematic viscosity is m^2/s.

vitrinite reflectance: the value typical for the maturity of the organic material and the maximum temperature of the sediment rock, based on measuring the light reflected vitrinite grains of the sedimentary rocks.

volcanics: rocks formed from magma erupted and/or effused on the surface.

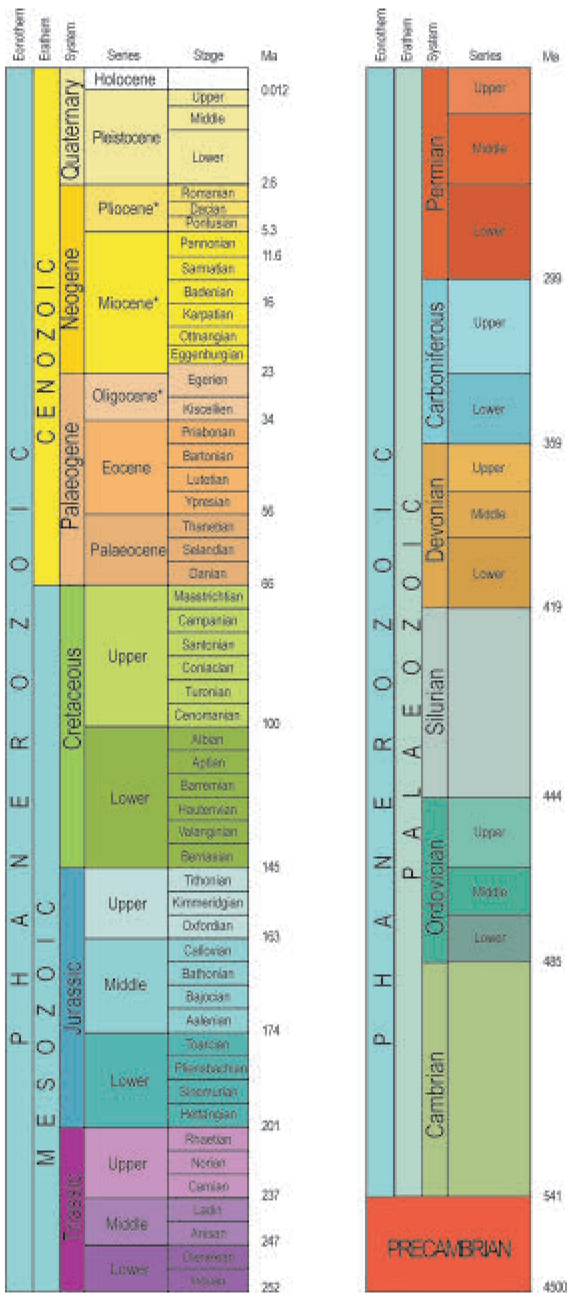
water body: related to the hydrocarbon reservoir. The water can be found under the hydrocarbon. Hydrocarbon and water contact is called the oil–water contact (OWC) or gas–water contact (GWC) according to the accumulated hydrocarbon type.

water drive crude oil reservoir: there is active water body located below oil body which displaces hydrocarbon during production. Oil–water contact (OWC) moves upward and water replaces hydrocarbon that moved to production well.

water reservoir: water filling up rock pores occurring under natural circumstances, its chemical content changes to a smaller or greater extent over time. Karstic water is reservoir water in limestone or dolomite fractures and with direct connection to surface waters.

water saturation: the percentage of total porosity of rock that is filled in by water.

wet gas: natural gas containing also some liquid hydrocarbon. The density of liquid produced with the gas is lower than 739 kg/m^3 and the gas–liquid ratio (GLR) can be between 1,068–17,800 m^3/m^3.



The geologic time scale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